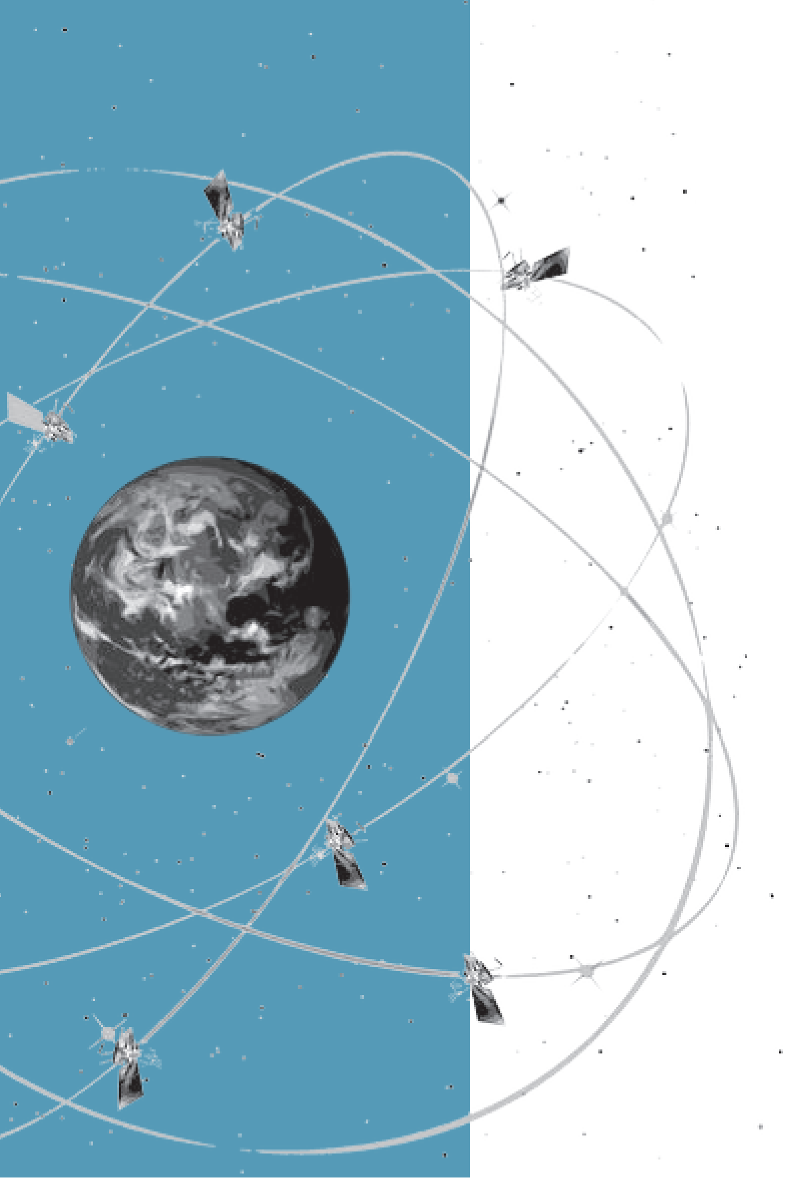
IGS INTERNATIONAL GNSS SERVICE

TECHNICAL REPORT 2017



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International GNSS Service

International Association of Geodesy
International Union of Geodesy and Geophysics

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Bern, Switzerland
Compiled in June 2018, by Arturo Villiger, Rolf Dach (Eds.)

Technical Report 2017

IGS Central Bureau

http://www.igs.org

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Published in June 2018

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IGS Technical Report 2017
ISSN: 2297-8526
ISBN: 978-3-906813-60-8 ; University of Bern, Bern Open Publishing.
DOI: 10.7892/boris.116377

Cite as:
Villiger, A., Dach, R. (eds.) (2018). *International GNSS Service Technical Report 2017 (IGS Annual Report).* IGS Central Bureau and University of Bern; Bern Open Publishing DOI 10.7892/boris.116377

Abstract

Applications of the Global Navigation Satellite Systems (GNSS) to Earth Sciences are numerous. The International GNSS Service (IGS), a voluntary federation of government agencies, universities and research institutions, combines GNSS resources and expertise to provide the highest–quality GNSS data, products, and services in order to support high–precision applications for GNSS–related research and engineering activities. This *IGS Technical Report 2017* includes contributions from the IGS Governing Board, the Central Bureau, Analysis Centers, Data Centers, station and network operators, working groups, pilot projects, and others highlighting status and important activities, changes and results that took place and were achieved during 2017.

This report is available in electronic version at
ftp://igs.org/pub/resource/pubs/2017_techreport.pdf.

The IGS wants to thank all contributing institutions operating network stations, Data Centers, or Analysis Centers for supporting the IGS. All contributions are welcome. They guarantee the success of the IGS also in future.

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IGS in 2017: The IGS Governing Board Chair Report

G. Johnston

IGS Governing Board Chair, Geoscience Australia

1 Introduction

In 2017 the IGS continued to evolve its work program to meet user and community needs. While delivery of the IGS core reference frame, orbit, clock and atmospheric products continues to drive the majority of activity, the IGS transformation to a multi-GNSS service continued with the harmonization of the MGEX network sites into the existing IGS network. The IGS has also engaged strongly in the ICG-IGS Joint Trial Project (IGMA) which aims to provide monitoring and assessment products for all GNSS constellations.

This year's IGS workshop was held in July 2017, and saw the geographical workshop journey return to Europe (France). The workshop was held on the campus of the University of Paris Diderot and was hosted jointly by IGN and CNES. The workshop centered on the theme of "Pathways to Improved Precision" and featured the stronger involvement of Galileo in the IGS and as a developing GNSS.

A revised Strategic Plan was finalized in late 2017, and aims to recognize the extensive contribution of the IGS participants, and to encourage strong engagement with a broader stakeholder set that now rely implicitly on IGS products and services.

The IGS proudly functions as a service of the International Association of Geodesy (IAG), and a contributor to the Global Geodetic Observing System (GGOS). Accordingly, a number of the Governing Board members continue to participate in IAG and GGOS governance, bureaus, commissions and working groups. Importantly, GB members also participate in the United Nations Global Geospatial Information Management (UN GGIM) efforts on Geodesy, which aims to enhance the sustainability of the global geodetic reference frame through intergovernmental advocacy for geodesy. GB members also routinely give presentations at the US PNT Advisory Board, influencing at the highest levels in the US government.

By working within the science community through (IAG/IUGG/ICSU) and the Intergovernmental community through ICG / UN GGIM / US PNT AB and others, the IGS GB ensures that the IGS retains its strong level of relevance and impact, and is sustainable.

2 The IGS at a Glance

A glance of the IGS is given in Figure 1.

3 IGS Highlights in 2017

3.1 New Global Data Centers in China and Spain

Wuhan University has been added as an IGS Global Data Center, and the GB officially endorsed fully-weighted adoption of Wuhan Rapid products. The Wuhan Data Center offers access to the full collection of IGS data and products to any user globally, especially those within the Asia Pacific Region. Importantly the data center gives direct access to the IGS data holdings to the very large research sector within China.

The European Space Agency's European Space Astronomy Centre (ESA ESAC) also became an IGS Global Data Center this year, and is based at ESAC in Madrid, Spain.

3.2 IGS 2017 Workshop in Paris, France

The latest IGS Workshop, with the theme of "Pathways to Improved Precision," took place 3-7 July, 2017. This workshop was hosted locally by the Institut National de l'Information Géographique et Forestière (IGN) and the Centre National d'ÃĽtudes Spatiales (CNES) at the University of Paris-Diderot in Paris, France. Almost 300 individuals from over 30 countries around the world participated in the sessions.

The workshop also featured a special keynote lecture on the Galileo system, given by Marco Falcone of the European Space Agency (ESA). Falcone's complete presentation, as well as videos of all other plenary presentations, and PDFs of posters, are available on the IGS website: http://www.igs.org/presents.

3.3 Planning for the 2018 IGS Workshop in Wuhan, China

In 2016, it was decided to move the workshops to an 18-month cycle, due to the wealth of topics and quickening pace of technological development impacting the IGS. Preparations are underway for the next IGS Workshop, taking place 29 October to 2 November 2018 in Wuhan, China. The workshop will be hosted by Wuhan University in China, and will be the first IGS Workshop on the Asian continent.

3.4 Membership Growth and Internal Engagement

In 2017, IGS membership reached 340 Associate Members, representing 118 countries. The 32-member IGS Governing Board guides the coordination of over 200 contributing organizations participating within IGS, including 106 operators of GNSS network tracking stations, 6 global data centers, 13 analysis centers, and 4 product coordinators, 28 associate analysis centers, 23 regional/project data centers, 13 technical working groups, two active pilot projects (i.e., Multi-GNSS and Real-time), and the Central Bureau.

Increased in-reach and engagement with the IGS Associate Membership took place, through the second open Associate Member meeting in December 2017, as well as increased activity with Associate Members via IGS social media platforms.

3.5 ICG Monitoring and Assessment

The IGMA ICG-IGS Joint Trial Project has experienced growth, and idea of using the existing monitoring infrastructure of IGS MGEX was introduced. The Trial Project established a Terms of Reference document, and has distributed Calls for Participation both geared toward ICG providers as well as the IGS community. The IGS Monitoring and Assessment Working Group was formed as a complement to the ICG-IGS Joint Trial Project.

4 IGS Operational Activities

4.1 Network Growth

As of the end of 2017, the IGS Network has 506 stations, of which 177 are multi-GNSS and 189 are real-time GNSS. Delivery of core reference frame, orbit, clock and atmospheric products continued strongly, with further refinement of the Real-Time Service and considerable efforts being targeted towards development of standards. Development of the IGS capacity to operate with multiple GNSSs also continued, with additional Galileo and BeiDou satellite launches bringing those constellations closer to operational status.

Over 500 IGS Network stations are maintained and operated globally by many institutions and station operators, making tracking data available at latencies ranging from daily RINEX files to real-time streams available for free public use. The transition of the IGS network to multi-GNSS capability has been led by the MGEX project team, with much assistance from the Central Bureau and Infrastructure Committee. The transition will has resulted in approximately 50% of IGS network stations being capable of tracking multiple GNSS constellations (GPS + GLONASS + one other) (September 2017). Within the network, 196 IGS stations are now capable of real-time data streaming in support of the IGS Real-Time Service.

4.2 Product Generation and Performance

Joint management of the IGS ACC by Michael Moore of Geoscience Australia and Tom Herring of the Massachusetts Institute of Technology continued, with operations based at Geoscience Australia in Canberra, Australia. The ACC combination software is housed on cloud based servers located in Australia and Europe, and coordination of the IGS product generation continues to be carried out by personnel distributed between GA and MIT. The IGS continues to maintain a very high level of product availability.

4.3 Adoption of IGS14 Reference Frame

The IGS adopted a new reference frame, called IGS14, on 29 January 2017 (GPS Week 1934). At the same time, an updated set of satellite and ground antenna calibrations, igs14.atx, was implemented. IGS14 is the latest in a series of GNSS reference frames adopted by the IGS. These reference frames form the basis of the IGS products, and are derived from each new version of the International Terrestrial Reference Frame. Updating to IGS14 will align IGS products to ITRF2014, and increase precision of that alignment by integrating additional available reference frame stations with more precise and up-to-date coordinates. For more information, please see [IGSMAIL-7399] “Upcoming switch to IGS14/igs14.atx.”and “IGS14/igs14.atx: a new framework for the IGS products.”

4.4 Antenna Calibration Updates

Coincident with the IGS14 Reference Frame release, IGS adopted antenna calibration updates in igs14.atx. These updates include robot calibrations for additional ground antenna types, increasing the percentage of ground stations in the IGS network with absolute calibrations to over 90%. This will result in increased coordinate accuracy for stations equipped with these antennas. SINEX and ANTEX files, as well as network maps, post-seismic deformation models, and offsets are available for download via ftp from Institut National de l’Information Géographique et Forestière (National Institute of Geographic and Forestry Information, IGN) and École Nationale des Sciences Géographiques (National School of Geographic Sciences, ENSG

4.5 Data Management

Data Management IGS product user activity documentation, courtesy of CDDIS, reveals that in 2017 (January-August), an average 106M GNSS files/12TB were downloaded per month; this includes GNSS data and product files. Focusing on IGS product files only, those totals are 26M GNSS product files/4.5TB on average per month. For Tropospheric downloads, CDDIS reports over 46M files totaling over 125 GB in 2016 from 500K unique hosts each month.

4.6 Standards Development Support

The IGS continues to contribute to the development of international standards related to GNSS, principally through participation within the RTCM (Radio Technical Commission for Maritime Service), where IGS leads the RINEX working group, as well as participating within the standards activities related to real time systems. Maintenance and further development of the RINEX data exchange standard continues to take place in cooperation with RTCM-SC104, and has led the recent release of RINEX 3.03.

4.7 Adoption of RINEX V3.04 and 9-Character Identification Format

The GB agreed to adopt the official RINEX V3.04 format, handling the ability for 9-character id and fixing the definition of GNSS reference time scales. The RINEX Working Group has assumed leadership in maintenance and further development of the RINEX data exchange standard, in cooperation with RTCM-SC104, and has led the recent release of RINEX 3.03. The RINEX Working Group has worked in cooperation with the IC to prepare a plan to transition from RINEX 2.x to RINEX 3.x. The IGS Network map was enhanced to provide information about stations providing data in RINEX 2 and RINEX 3 formats, which may be viewed in real time at: http://www.igs.org/network

Data Center Working Group is working on integrating long filenames, RINEX3 data into operational archives. The Troposphere WG is also incorporating long names in its SINEX.

4.8 Completion of IGS Web-Based Assets to IGS.org

The IGS website, product servers, FTP, and mailing lists were updated to reflect the transition from igscb.jpl.nasa.gov to IGS.org. This was the last step in the three-year transition process. More information about this transition may be found here: http://www.igs.org/article/igs-website-server-ftp-and-mailing-list-transitions

5 IGS Governing Board Meetings in 2017

The Governing Board discusses the activities and plans of various IGS components, sets policies, and monitors the progress with respect to the agreed strategic plan and annual implementation plan. It is customary to hold two GB meetings during any IGS Workshop – the second of which typically focusing on workshop recommendations and other debriefing from the week's activity.

23 April 2017	Governing Board Business Meeting, held prior to the 2017 European Geosciences Union meeting	Vienna, Austria
2 July 2017	48þGoverning Board Meeting (1 of 2 sessions), held immediately before the 2017 IGS Workshop	Paris, France
7 July 2017	48þGoverning Board Meeting (2 of 2 sessions), held immediately after the 2017 IGS Workshop	Paris, France
11 December 2016	49þGoverning Board Meeting, held prior to the 2017 American Geophysical Union meeting	New Orleans, Louisiana, United States

6 IGS Advocacy, and External Engagement

6.1 United Nations GGIM Sub-Committee on Geodesy

IGS remains active in engaging with diverse organizations that have an interest in geodetic applications of GNSS. Notably, the IGS has supported the development of the Global Geodetic Reference Frame (GGRF) resolution, roadmap, and upcoming implementation plan within the United Nations (UN) Global Geospatial Information Management (GGIM) Committee of Experts (http://ggim.un.org).

6.2 United States PNT Advisory Board

IGS actively engages and participates in the United States National Space-Based Positioning, Navigation, and Timing (PNT) Advisory Board (http://www.gps.gov/governance/advisory/). Both Central Bureau Director Ruth Neilan (NASA JPL, United States) and former Governing Board member Gerhard Beutler (AIUB, Switzerland) are members of this board, which provides advice to the US Government Executive Committee, chaired by the United States Deputy Secretary of Defense and Deputy Secretary of Transportation.

Beutler gave presentations focusing on Multi-GNSS at both June and November 2017 PNT meetings. IGS Governing Board members are often invited guests of the PNT, presenting on key contemporary issues as well as reflecting on decades of work.

6.3 International Association of Geodesy Executive Participation

The IGS is represented in a variety of roles throughout the geodetic community. Board member and Central Bureau Director Ruth Neilan and GB member Richard Gross serve as members of the International Association of Geodesy (IAG) Executive Committee.

IGS Governing Board Members served on the Coordinating Board, Executive Committee, Consortium, and Science Panel of the IAG Global Geodetic Observing System (GGOS). Several of these members participated in the annual GGOS Days series of meetings, held at the Bundesamt für Eich- und Vermessungswesen (Federal Agency for Metrology and Surveying, Austria) headquarters and the Technische Universität Wien (Technical University of Vienna) in Vienna, Austria.

6.4 Communications Development and Guidance

Communications, advocacy, and public information activities continued to develop in 2017, including a communications interest and development session held at the Paris Workshop, and a second associate member and working group open meeting held 10 December prior to the Governing Board meeting at AGU in New Orleans.

Web and printed content continue to be developed and refreshed. A new IGS Brochure was developed to complement the recently revised 2017 Strategic Plan. Numerous news pieces covering IGS contributing organizations, IGS activities, and other announcements were developed in collaboration with Governing Board members and their respective contributing organizations. Governing Board members also began an initiative to connect their agency or organization's social media or communications teams with the Central Bureau to ensure optimal collaboration and mutual public relations support.

7 Outlook 2018

In 2018 the IGS workshop participants will travel to China, with the workshop being held in Asia for the first time. Wuhan University will host the workshop, which offers an exciting opportunity for the IGS to expose the excellent science undertaken within the IGS to a large and captive audience of researchers from China and Asia more generally. With the workshop being in China, a focus on Beidou development is likely to feature as well as the ongoing IGS work plan related issues.

The IGS will continue to be challenged by the growing stakeholder expectations for improved product timeliness, fidelity and diversity. As these are achieved reconsideration of the IGS mission and goals will need to be undertaken to ensure we don't become tangential to the needs of our key stakeholders, the associate members. Continued efforts to enhance advocacy for the IGS are needed, with the GB and CB playing key roles in this, but not at the exclusion of all associate members. Accordingly, presentations at a variety of forums within our discipline and outside of it will need to be given, ensuring that the efforts of all contributors are acknowledged. In this way the IGS will continue to build its user base resulting in enhanced sustainability.

Lastly, the GB thanks all participants within the IGS for the efforts, with particular thanks going to those working group chairs ending their current terms. Without the contributions of all, the IGS could not have achieved the significant outcomes detailed in this report.

Figure 1: The IGS at a Glance.

IGS Central Bureau Technical Report 2017

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1 Introduction

The mission of the IGS Central Bureau (CB) is to provide continuous management and technology in order to sustain the multifaceted efforts of the IGS in perpetuity. It functions as the executive office of the Service and responds to the directives and decisions of the IGS Governing Board. The CB coordinates the IGS tracking network and operates the CB information system (CBIS), the principal information portal where the IGS web, ftp and mail services are hosted. The CB also represents the outward face of IGS to a diverse global user community, as well as the general public. The CB office is hosted at the California Institute of Technology/Jet Propulsion Laboratory, Pasadena, California, USA. It is funded principally by the US National Aeronautics and Space Administration (NASA), which generously contributes significant staff, resources, and coordination to advance the IGS. The following report highlights progress made by the Central Bureau in 2017.

2 Executive Management and Governing Board Participation

In response to personnel changes in 2017, the Central Bureau created an IGS Central Bureau Operations Plan describing the roles, responsibilities, and deliverables of each member of the CB and of the CB as a whole. These descriptions expand on and are consistent with description of the CB in the IGS Terms of Reference. The Operations

Plan was provided to the IGS Governing Board Chair and made available to members of the Governing Board for review and comment.

Governing Board (GB) meetings were held in April (Vienna), July (Paris), and December (New Orleans) 2017. The Executive Committee (EC) met additionally by teleconference approximately every other month. Staff of the Central Bureau, as part of its work program carrying out the business needs of the IGS, implemented actions defined by the Governing Board throughout the year. This included a thorough analysis and refresh of the IGS Terms of Reference.

The CB supported the ongoing update of the Associate Members list in preparation of the Governing Board elections. The IGS Associate Members form the body of voters who elect the Governing Board, and play a vital role in the ongoing success and sustainability of the service. Associate Member and Governing Board Member lists are maintained by the CB on the IGS website (http://igs.org/about/organization).

The CB also continued to play an active role in supporting the organization of regular IGS Workshops, participating in preliminary meetings of both local and scientific organizing committee members for the 2017 Paris workshop. These meetings took place in person in April (Vienna) and December (New Orleans) as well as via email and teleconference, as well as providing support during the Workshop. In addition, the CB initiated contact with leadership organizing the IGS Workshop to be held in Wuhan China, in October and November 2018 to offer support and guidance in the workshop planning process.

3 Strategic Planning and Progress

The Central Bureau worked closely with members of the Governing Board Executive Committee to ensure any remaining feedback regarding the 2017 Strategic Plan was addressed. The revised Strategic Plan was finalized in late 2017, and will be published in early 2018.

4 Communications, Advocacy, and Public Information

The Central Bureau continued to develop communications, advocacy, and public information initiatives on behalf of the Governing Board. Central Bureau members also led a communications interest and development session at the Paris Workshop. Similar sessions will be held at upcoming workshops and in complement to other IGS activities, when relevant.

Associate membership engagement continued with the second open Associate Member meeting held prior to the December Governing Board meeting. The meeting was open to all associate members and observers, and featured presentations by the Wuhan Workshop Local Organizing Committee, working group chairs, and other IGS components. Future engagement sessions, targeted at long-term development of the associate membership, will be planned in conjunction with major conferences, such as AGU, EGU, and IAG symposia.

The Central Bureau actively works with other IAG components to promote communications and outreach, including the IAG Communications and Outreach Branch and GGOS Coordinating Office. As representatives of the IAG, IGS CB members also participate actively in the United Nations Initiative on Global Geospatial Information Management (GGIM) Sub-Committee on Geodesy, Focus Group on Outreach and Communications.

Social media has been actively maintained by CB staff and grew significantly in 2017, due in part by growing and maintaining mutually beneficial links to IGS Contributing Organization communications representatives and increased frequency of posting, as well as enhanced content. Increased cross-linking with IGS website and knowledge base content, as well as promoting video resources available at IGS/presents, will continue in 2018.

5 Network Coordination

The IGS network added 11 stations and decommissioned 10 stations in 2017, bringing the total to 506 stations. The development of a multi-GNSS sub-network within the greater IGS network is led by the MGEX Project, which develops the IGS's capability to operate with multiple GNSS constellations and has 217 multi-GNSS capable (GPS+GLONASS+one other) stations. Additionally, the number of IGS stations now ca-

Figure 1: Network map from http://igs.org/network.

pable of real-time data streaming in support of the IGS Real-Time Project has increased to 195.

6 Web Development and Information Technology Support

In addition to administration and general support of CBIS operation, the Central Bureau has continued moving IT services to external cloud hosted servers, in order to allow global access. IGS Product access was redirected from IGS CB mirrors to the Crustal Dynamics Data Information System (CDDIS, ftp://cddis.gsfc.nasa.gov/gnss/products/), Institut National de l'Information Géographique et Forestière (IGN, ftp://igs.ensg.ign.fr/pub/igs/products/) and Scripps Institution of Oceanography (SIO, ftp://garner.ucsd.edu/pub/products/) to ensure global access to over 20 years of analysis products, as well as enabling access to data. The IGS also moved its Real Time Service (RTS) caster to a supercomputing center to ensure performance, availability, and service monitoring.

Regular improvements and enhancements to the IGS.org website have taken place, with further improvement in working group subdomains. These improvements will enable working group membership to manage their own content, in addition to working with CB development and communications staff. IGS Contributing Organizations will also be provided with editable pages in IGS.org in order to best communicate their individual contributions to, and benefit from, the Service. All other references to the old IGSCB website have been redirected to or reestablished on IGS.org or the IGS Knowledge Base.

Content and resources in the IGS Knowledge Base, http://kb.igs.org, continue to be enhanced and expanded. The Knowledge Base also includes task tracking and ticketing platform for Central Bureau projects and work, as well as user feedback and requests. Comments, suggestions, and other feedback are now welcomed through standardized "contact us" and "feedback" forms, whose links are available at the foot of each page on IGS.org.

IGS social media has also been integrated throughout the website, to facilitate sharable content and optimize engagement with IGS stakeholders. IGS audio-visual resources, made available through IGS Presents, were upgraded to include video playback integration. Workshop resources, including images, posters, presentation slides, and videos, also continue to be made available on IGS Presents, which now also displays usage metrics such as the number of times a particular video has been viewed.

7 Project, Committee and Working Group Support and Participation

The Central Bureau provides administrative and information technology support to IGS Working Groups, and has been involved in aspects of the following initiatives:

- Initiation of IGMA initial test campaign.
- Development of a Troposphere comparison site.
- Full integration of Multi-GNSS stations into the IGS Network.
- Advocating for RINEX 3.03 and its support of all GNSS constellations.
- Development of a UNAVCO prototype for GeodesyML output from the IGS Site Log Manager system.
- Support of 2017 Governing Board elections.
- Verification of IGS Associate Member contact information and participation through both personal and a newly-developed automated process.

CB staff met with the Infrastructure Committee Chair roughly once per month on a range of station and infrastructure management issues.

8 Governing Board Elections Support

Elections for the Governing Board positions of Network Representative and Data Center Representative took place in the latter half of 2017. CB staff worked with the GB Elections Committee to ensure nominations and voting processes were successful. In parallel to this, the CB worked to develop a system, first manual and then automated, of Associate Member contact information and participation status verification.

9 IGS Workshop Support

In preparation for the 2017 Paris Workshop, the Central Bureau provided support and guidance to members of the Workshop local and scientific organizing committees. During the Workshop, CB staff video recorded all plenary presentations, maintained a continuous social media presence, and supported both GB and Working Group splinter meetings. All presentation material is available on the IGS website: http://www.igs.org/presents/workshop2017.

Refined Workshop timelines, logistical lessons learned, and other key organizational information was developed after the close of the 2017 Paris Workshop and delivered to the local and scientific organizing committee representatives of the 2018 Wuhan Workshop. Support for the planning and organization of this workshop, taking place 29 October to 2 November 2018 in Wuhan, China, will continue throughout 2018.

10 IGS User Support

The CB expends considerable effort on IGS community and user technical support. As measure of this, the CB tracks email traffic through the CB mail list. This traffic has increased by 15% in 2017 to about 650 messages, though much of the increase is from notification emails from various CBIS processes that do not require response.

In an effort to make user support more efficient, the Central Bureau continues to route many of its inquiries through a support ticketing system coupled with the Knowledge Base section of the IGS website. This system tracked over 800 support issues that were resolved through the year. Enhancement of online information resources, organized mainly in the Knowledge Base, has continued to relieve some of the email-based support that the CB has historically provided.

11 External Participation

The Central Bureau participates in, and interacts with, many IGS stakeholder organizations. A continuing highlight is the CB staff activity within the United Nations GGIM Sub-Committee on Geodesy (formerly Global Geodetic Reference Frame Working Group). For more information, please visit the UN-GGIM website: http://ggim.un.org/UN_GGIM_wg1.html .

Significant progress was also made in supporting the development of a cooperative plan with the United Nations Office for Outer Space Affairs (UNOOSA), International Committee on Global Navigation Satellite Systems (ICG) to monitor performance and interoperability metrics between the different GNSSs, which is now embodied by a joint IGS-ICG working group on monitoring and assessment.

The CB Director and staff members have continued to represent the IGS the within IAG service committees and boards, including R. Neilan on the GGOS Coordinating Board and Executive Committee.

The CB Director continues to serve the US Federal Advisory Board for Space-based Position, Navigation and Timing, as the appointed NASA representative. Other IGS representatives presenting at the PNT Advisory Board meetings include IGS Founding Governing Board Chairman Professsor Gerhard Beutler (University of Bern, Switzerland). To view presentations made at PNT Advisory Board meetings, please visit: http://www.gps.gov/governance/advisory/ .

12 Publications

- IGS 2016 Technical Report, IGS Chapter.

- NASA SGP/ICPO annual progress update, NASA internal publication.
- Johnston, G., Neilan, R., Fisher, S., Rizos, C., Meertens, C., Dach, R., and Craddock, A. (2017, April). International GNSS Service Update. Poster session presented at the meeting of the European Geosciences Union General Assembly, Vienna, Austria.

Part II

Analysis Centers

Analysis Center Coordinator Technical Report 2017

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1 Product Quality and Reliability

For 2017, with a few exceptions the delivery of ultra-rapid and rapid products have been well within the expected latencies. There has been an ongoing issue in the latency of the final products, this has mainly be due to the requirement of manual intervention in the generation of the product.

1.1 Ultra-rapid

Currently the IGS is receiving 8 submissions from different ACs for combined IGS ultra-rapid products (see Table 1). The combined IGS ultra-rapid can be split into two components, a fitted portion based upon observations, and a predicted component reliant upon forward modelling of the satellite dynamics.

The fitted portion of the ultra-rapid orbits continue to agreeing to the rapid orbits at the level of 8 mm (see Figure 1) and has been consistently at this level since GPS week 1500. There continues to be an improvement in the agreement between the ultra-rapid predicted orbits compared to the IGS rapid orbits (see Figure 2). This is indicative that there has in fact been an improvement in the orbit modelling amongst all of the contributing ACs.

There are some interesting variations, in the predictive component, that indicate further improvement could be achieved by most ACs. In one instance in GPS week 1978, DoW 6, Hour 06, for PRN 19 (a Block IIR-'B' satellite) performed poorly in the ultra-rapids submissions from many ACs (see Table 2). Unusually this was in the period immediately after the satellites eclipsing period. However, for this instance, good results were still achieved by ESA and GFZ.

Table 1: ACs contributing to the Ultra-rapid products, W signifies a weight contribution, C is comparison only, and S is suspended

Analysis Centre	SP3	ERP	CLK
CODE	W	W	W
EMR	W	W	W
ESA	W	W	W
GFZ	W	W	W
NGS	S	S	S
SIO	W	W	C
USNO	W	W	C
WHU	C	C	C

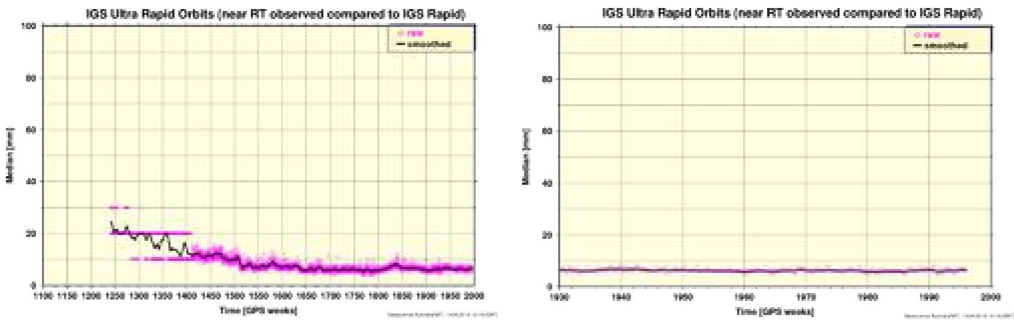

Figure 1: The median difference of the fitted component of the IGS ultra-rapid combined orbits with respect to the IGS rapid orbits.

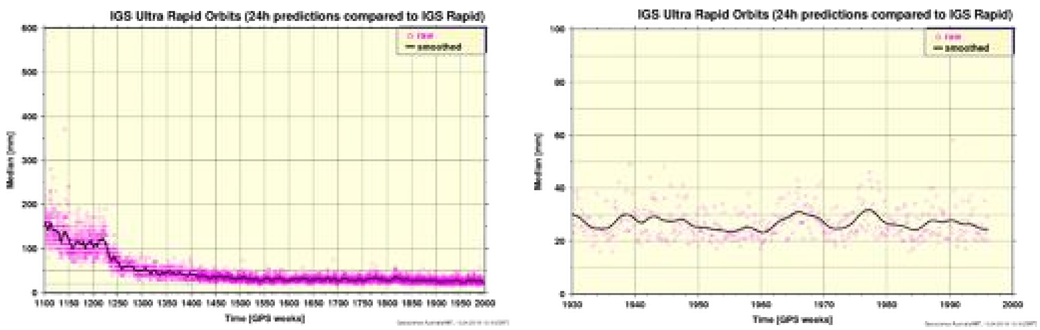

Figure 2: Median of IGU combined predicted orbits compared to IGR

Table 2: Fit for each satellite and each centre resulting from the comparison of the individual solutions to the IGS Rapid solution. (first 6 hours of prediction) from Table 2.1978.6

PRN	brd	cou	emu	esu	gfu	siu	usu	uxv	whu	igu	igr	IGR
1	647	12	24	27	20	13	39	50	16	15	0	0
2	733	18	19	16	21	49	20	13	33	13	0	0
3	691	29	23	22	26	53	45	68	19	25	0	0
4	88045	25	—	—	—	—	—	—	—	—	0	0
5	618	20	20	17	21	18	32	71	15	17	0	0
6	477	18	24	14	12	18	41	38	63	8	0	0
7E	1209	12	17	16	26	106	32	40	25	9	0	0
8	170	19	17	21	16	55	26	29	30	12	0	0
9	1685	38	19	22	14	21	41	19	30	24	0	0
10	882	13	16	14	21	44	19	41	27	9	0	0
11E	536	30	38	42	13	35	42	27	38	32	0	0
12	817	6	21	28	11	32	33	34	31	12	0	0
13	561	9	16	14	26	30	27	35	48	5	0	0
14	741	18	30	45	31	62	23	33	21	25	0	0
15	289	44	47	21	49	20	56	37	19	39	0	0
16	555	15	13	20	12	64	22	25	24	11	0	0
17	431	24	17	17	25	38	22	49	49	12	0	0
18	740	26	12	13	17	19	34	36	27	9	0	0
19	**527**	**132**	**191**	**13**	**24**	**42**	**163**	**63**	**251**	**162**	**0**	**0**
20	574	15	7	16	25	14	30	67	26	9	0	0
21	410	30	11	11	21	42	22	28	29	12	0	0
22	471	18	21	17	17	25	36	43	13	12	0	0
23	635	20	30	19	14	75	38	43	33	7	0	0
24E	475	15	23	12	30	22	45	53	36	16	0	0
25	477	12	19	12	14	12	32	47	26	12	0	0
26	169	14	13	12	15	12	23	33	24	8	0	0
27	542	9	12	10	9	18	29	—	35	4	0	0
28	1684	15	11	19	18	48	16	20	9	8	0	0
29	1472	23	27	9	15	73	25	46	77	16	0	0
30E	326	20	20	24	34	66	24	45	37	12	0	0
31E	1092	22	15	21	43	42	30	53	36	13	0	0
32	618	14	29	16	22	22	31	34	17	19	0	0
RMS	15583	31	40	20	23	44	43	43	56	33	0	-
WRMS	15583	19	22	20	23	38	37	42	33	18	0	-
MEDI	574	18	19	17	21	35	31	38	29	12	0	-

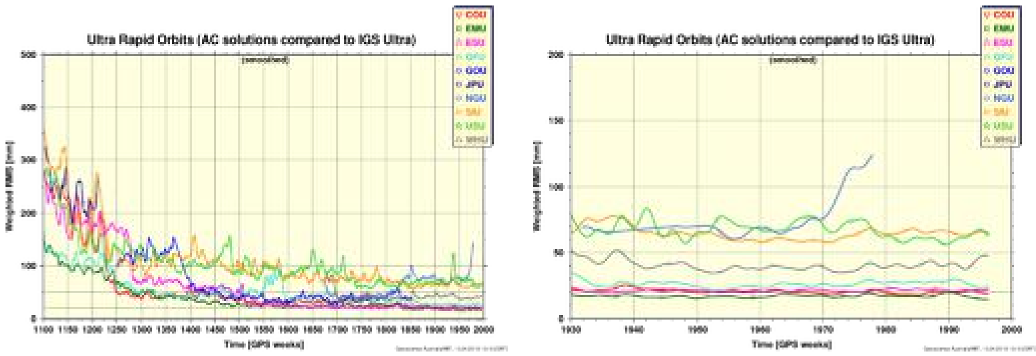

Figure 3: Median of AC Ultra-rapid predicted orbits compared to IGR

The contribution from NGS has been de-weighted since week 1974, due to a rapid decline in the predictive performance of their submitted ultra-rapid orbits (see Fig 3). They are currently investigating the cause, and suspended their submissions until recently GPS Week 1997 are now submitting their solutions for comparison only at this stage. Once the NGS solution returns back to a good comparison level with other ACs for a reasonable period of time then we will look at re-weighting their submissions. Our intention is to also take a closer look at the Wuhan submissions to assess if they can become a weighted solution for ultra-rapid products in the future.

1.2 Rapid

There has been no significant change in the difference between the combined IGS rapid orbits and the combined IGS final orbits. This has consistently been at a level of 6-7 mm since GPS week 1500.

1.2.1 Changes to be made to products

Wuhan changed from a comparison only submissions to a weighted solution from GPS week 1959, DoW 1. We are proposing to make a couple of adjustments to the weighting of the rapid combination submissions. As there are potentially three changes to the product, each individual change will be implemented over an extended period.
Initially we plan to re-weight the CODE ERP solution back into the rapid products. An experimental recombination of 20 weeks of rapid solutions, with the CODE ERP submissions fully weighted did not have any noticeable detrimental impact upon the combined products. We also plan to weight the ERP submissions from USNO. However this will require that their orbits are also weighted. This is due to a requirement in the current

Table 3: ACs contributing to the Rapid products, *W* signifies a weight contribution, *B* broadcast clock, *C* is comparison only, and *S* is suspended

Analysis Centre	SP3	ERP	CLK
CODE	W	C	W
EMR	W	W	W
ESA	W	W	W
GFZ	W	W	W
JPL	W	W	W
NGS	W	B	W
SIO	W	C	C
USNO	C	C	C
WHU	W	W	C

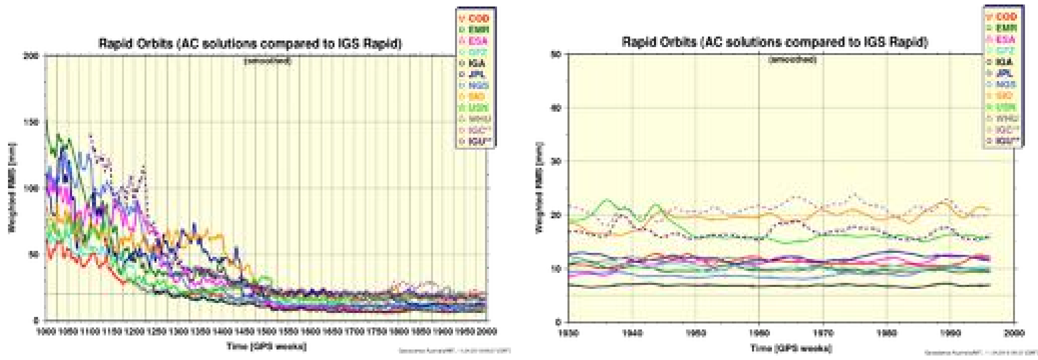

Figure 4: Weighted RMS of ACs Rapid orbit submissions (smoothed)

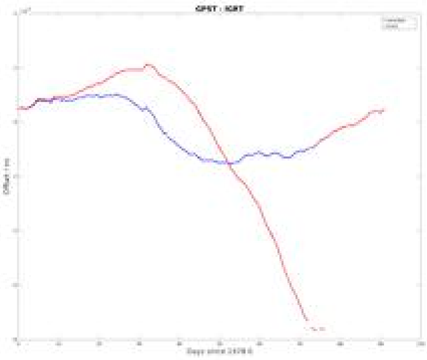

Figure 5: Difference between GPST and the IGR Time scale. The red line depicts the difference in the time scales between GPST and IGRT obtained from the original combined IGS rapid clocks. The blue line shows the re-aligned rapid clocks following recombination

version of the combination code for the ERP solution to be combined, the orbit solution must also be weighted contribution. This will require further analysis to confirm the stability of the combined IGS rapid solution is maintained for the Orbit and ERP products. We are also proposing to start weighting the Wuhan clock solution.

1.3 Issues with time alignment in rapid products

There has been an issue with the alignment of the rapid time scale. We have observed large variations in the IGRT exceeding the 20 ns bounds (see figure 5). To fix the problem the rapid clocks had to be re-combined from GPS week 1978 through to 1988, and resubmitted to the data centres. Currently work is being carried out by Michael Coleman to adjust the code use to align the rapid time scale to help prevent further issues with the rapid time scale.

1.4 Final

Most AC final solutions are comparing at less than 5 mm to each other (see Figure 6). Since the implementation of IGS14 JPL have requested to be set as comparison only. Once they have completed their reprocessing run we will look at weighting their solutions into the combined products.

Table 4: ACs contributing to the Final products, W signifies a weight contribution, C is comparison only

Analysis Centre	Orbit	ERP	Clock
CODE	W	C	W
EMR	W	W	W
ESA	W	W	W
GFZ	W	W	W
GRG	W	W	W
JPL	C	C	C
MIT	W	W	C
NGS	W	W	W
SIO	W	C	W

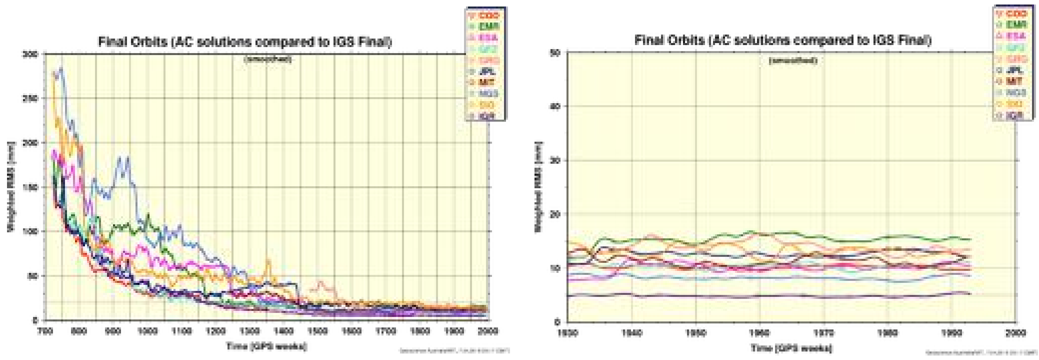

Figure 6: Weighted RMS of IGS Final orbits (smoothed)

1.5 Latency of Final products

There has been an issue in producing the final products within the specified time period. Generation of the final product is a manual process which involves contribution from three different agencies. The first step is to put together a new reference frame combination, run by IGN using CATREF. The time to complete a reference frame combination of over 15 years is now taking significantly longer, as the time span and number of stations has increased markedly. Once the updated IGS reference has been completed these solutions are passed onto the ACC to constrain the orbit and clock products. Once a combination has been completed, a clock alignment is computed by NRL and passed back to the ACC. Even though this process is automated it can take several hours to complete. Once the result have been automatically transferred back to the ACC server the results are manually verified before they are applied to the final products and released for publication.

IGN have implemented a solution that allows the release of the final SINEX file need by the ACC at an earlier stage in the process, and this has helped to improve the latency of the final product, but the manual nature and interconnected processes from different agencies can still lead to delays, which is further exacerbated by time zone differences between the different agencies.

2 Updates to ACC Combination Software

The source code used to perform the combination has been adapted to allow it to be compilable by gcc. This removes a dependency upon the lahey compiler, so we no longer have to consider having a commercial licence available to recompile or make modifications to the software. This has allowed us to start looking at the source code to make some minor modifications to allow it to accept SP3D files.

3 Preparation for next ITRF

There has been a request from the IERS to for a list of models to be considered for the next version of ITRF, along with an indication on the length of time it would take to complete a reprocessing run.

In general the majority of ACs state they will not be in a position to attempt to start another reprocessing effort until the end of 2019, beginning of 2020. We anticipate we will need at least 6 months for the ACS to complete a re-processing run. This is assuming that all of the models to be implemented have been agreed upon by the end of 2018.

1. IERS Conventions and updates.
2. Implemented linear mean pole model

3. Develop and implement diurnal and subdiurnal tidal EOP models based on recommendations from the working group.
4. Adopt post EGM2008 static gravity field based on all GRACE & GOCE data and the Highest-fidelity time-variable gravity (TVG) model using GRACE + SLR + geophysical fluid models, consistent with GRACE + GOCE standards. We need to stay consistent with the models applied by other techniques.
5. Most ACs would prefer to not apply a loading model, those that do, do not think that their preferred model can be implemented in time for a re-processing effort.
6. Continue investigations into the cause of 13.66 d signal in GNSS time series & fix tide model responsible.
7. Research near-field signal multipath & develop methods to calibrate in-situ position biases at all reference frame stations, but we are unlikely to have a solution in place in time for the next reprocessing effort.
8. Continue investigating methods to mitigate pervasive draconitic signal.
9. Continue improvement in radiation force modelling
10. Minimize equipment- and local-induced position offsets
11. ACs should utilizing RINEX3 observations where possible, while DCs should maintaining/preserving historic access to RINEX2 observations

Additional Comments

Several ACs have stated that they are prepared to submit a Multi-GNSS solution as part of their reprocessing effort. We are looking at the issue of allowing variable orbit arc lengths to be utilized by the different ACs.

We have started to set up a web site to detail the potential models to be used for a third reprocessing effort `http://acc.igs.org/repro3.html`. This will be updated over time.

Center for Orbit Determination in Europe (CODE) Technical Report 2017

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1 The CODE consortium

CODE, the Center for Orbit Determination in Europe, is a joint venture of the following four institutions:

- Astronomical Institute, University of Bern (AIUB), Bern, Switzerland
- Federal Office of Topography swisstopo, Wabern, Switzerland
- Federal Agency of Cartography and Geodesy (BKG), Frankfurt a. M., Germany
- Institut für Astronomische und Physikalische Geodäsie, Technische Universität München (IAPG, TUM), Munich, Germany

The operational computations are performed at AIUB, whereas IGS–related reprocessing activities are usually carried out at IAPG, TUM. All solutions and products are generated with the latest development version of the Bernese GNSS Software (Dach et al. 2015a).

2 CODE products available to the public

A wide range of GNSS solutions based on a rigorously combined GPS/GLONASS data processing scheme is computed at CODE. The products are made available through anonymous ftp at – please note the URL-change of the FTP server:
ftp://ftp.aiub.unibe.ch/CODE/ or http://www.aiub.unibe.ch/download/CODE/
An overview of the files is given in Table 1.

Within the table the following abbreviations are used:

yyyy	Year (four digits)	ddd	Day of Year (DOY) (three digits)
yy	Year (two digits)	wwww	GPS Week
yymm	Year, Month	wwwwd	GPS Week and Day of week

Table 1: CODE products available through anonymous ftp.

CODE *final* products available at ftp://ftp.aiub.unibe.ch/CODE/yyyy/	
yyyy/CODwwwwd.EPH.Z	CODE final GPS and GLONASS orbits
yyyy/CODwwwwd.ERP.Z	CODE final ERPs belonging to the final orbits
yyyy/CODwwwwd.CLK.Z	CODE final clock product, clock RINEX format, with a sampling of 30 sec for the GPS&GLONASS satellite and reference (station) clock corrections and 5 minutes for all other station clock corrections
yyyy/CODwwwwd.CLK_05S.Z	CODE final clock product, clock RINEX format, with a sampling of 5 sec for the GPS&GLONASS satellite and reference (station) clock corrections and 5 minutes for all other station clock corrections
yyyy/CODwwwwd.SNX.Z	CODE daily final solution, SINEX format
yyyy/CODwwwwd.TRO.Z	CODE final troposphere product, troposphere SINEX format
yyyy/CODGddd0.yyI.Z	CODE final ionosphere product, IONEX format
yyyy/CODwwwwd.ION.Z	CODE final ionosphere product, Bernese format
yyyy/CODwwww7.SNX.Z	CODE weekly final solution, SINEX format
yyyy/CODwwww7.SUM.Z	CODE weekly summary file
yyyy/CODwwww7.ERP.Z	Collection of the 7 daily CODE-ERP solutions of the week
yyyy/COXwwwwd.EPH.Z	CODE final GLONASS orbits (for GPS weeks 0990 to 1066; 27-Dec-1998 to 17-Jun-2000)
yyyy/COXwwww7.SUM.Z	CODE weekly summary files of GLONASS analysis
yyyy/CGIMddd0.yyN.Z	Improved Klobuchar–style ionosphere coefficients, navigation RINEX format
yyyy/P1C1yymm.DCB.Z	CODE monthly P1−C1 DCB solution, Bernese format, containing only the GPS satellites
yyyy/P1P2yymm.DCB.Z	CODE monthly P1−P2 DCB solution, Bernese format, containing all GPS and GLONASS satellites
yyyy/P1P2yymm_ALL.DCB.Z	CODE monthly P1−P2 DCB solution, Bernese format, containing all GPS and GLONASS satellites and all stations used
yyyy/P1C1yymm_RINEX.DCB	CODE monthly P1−C1 DCB values directly extracted from RINEX observation files, Bernese format, containing the GPS and GLONASS satellites and all stations used
yyyy/P2C2yymm_RINEX.DCB	CODE monthly P2−C2 DCB values directly extracted from RINEX observation files, Bernese format, containing the GPS and GLONASS satellites and all stations used

Table 1: CODE products available through anonymous ftp (continued).

CODE *rapid* products available at ftp://ftp.aiub.unibe.ch/CODE

CODwwwwd.EPH_M	CODE final rapid GNSS orbits
CODwwwwd.EPH_R	CODE early rapid GNSS orbits
CODwwwwd.EPH_P	CODE 24–hour GNSS orbit predictions
CODwwwwd.EPH_P2	CODE 48–hour GNSS orbit predictions
CODwwwwd.EPH_5D	CODE 5–day GNSS orbit predictions
CODwwwwd.ERP_M	CODE final rapid ERPs belonging to the final rapid orbits
CODwwwwd.ERP_R	CODE early rapid ERPs belonging to the early rapid orbits
CODwwwwd.ERP_P	CODE predicted ERPs belonging to the predicted 24–hour orbits
CODwwwwd.ERP_P2	CODE predicted ERPs belonging to the predicted 48–hour orbits
CODwwwwd.ERP_5D	CODE predicted ERPs belonging to the predicted 5–day orbits
CODwwwwd.CLK_M	CODE GNSS clock product related to the final rapid orbit, clock RINEX format
CODwwwwd.CLK_R	CODE GNSS clock product related to the early rapid orbit, clock RINEX format
CODwwwwd.TRO_R	CODE rapid troposphere product, troposphere SINEX format
CODwwwwd.SNX_R.Z	CODE rapid solution, SINEX format
CORGddd0.yyI	CODE rapid ionosphere product, IONEX format
COPGddd0.yyI	CODE 1–day or 2–day ionosphere predictions, IONEX format
CODwwwwd.ION_R	CODE rapid ionosphere product, Bernese format
CODwwwwd.ION_P	CODE 1–day ionosphere predictions, Bernese format
CODwwwwd.ION_P2	CODE 2–day ionosphere predictions, Bernese format
CODwwwwd.ION_P5	CODE 5–day ionosphere predictions, Bernese format
CGIMddd0.yyN_R	Improved Klobuchar–style coefficients based on CODE rapid ionosphere product, RINEX format
CGIMddd0.yyN_P	1–day predictions of improved Klobuchar–style coefficients
CGIMddd0.yyN_P2	2–day predictions of improved Klobuchar–style coefficients
CGIMddd0.yyN_P5	5–day predictions of improved Klobuchar–style coefficients
P1C1.DCB	CODE sliding 30–day P1−C1 DCB solution, Bernese format, containing only the GPS satellites
P1P2.DCB	CODE sliding 30–day P1−P2 DCB solution, Bernese format, containing all GPS and GLONASS satellites
P1P2_ALL.DCB	CODE sliding 30–day P1−P2 DCB solution, Bernese format, containing all GPS and GLONASS satellites and all stations used
P1P2_GPS.DCB	CODE sliding 30–day P1−P2 DCB solution, Bernese format, containing only the GPS satellites
P1C1_RINEX.DCB	CODE sliding 30–day P1−C1 DCB values directly extracted from RINEX observation files, Bernese format, containing the GPS and GLONASS satellites and all stations used
P2C2_RINEX.DCB	CODE sliding 30–day P2−C2 DCB values directly extracted from RINEX observation files, Bernese format, containing the GPS and GLONASS satellites and all stations used
CODE.DCB	Combination of P1P2.DCB and P1C1.DCB
CODE_FULL.DCB	Combination of P1P2.DCB, P1C1.DCB (GPS satellites), P1C1_RINEX.DCB (GLONASS satellites), and P2C2_RINEX.DCB
CODE.BIA	Same content but stored as OSBs in the bias SINEX format

Note, that as soon as a final product is available the corresponding rapid, ultra–rapid, or predicted products are removed from the anonymous FTP server.

Table 1: CODE products available through anonymous ftp (continued).

CODE *ultra–rapid* products available at `ftp://ftp.aiub.unibe.ch/CODE`

`COD.EPH_U`	CODE ultra–rapid GNSS orbits
`COD.ERP_U`	CODE ultra–rapid ERPs belonging to the ultra–rapid orbit product
`COD.TRO_U`	CODE ultra–rapid troposphere product, troposphere SINEX format
`COD.SNX_U.Z`	SINEX file from the CODE ultra-rapid solution
`COD.SUM_U`	Summary of stations used for the latest ultra–rapid orbit
`COD.ION_U`	Last update of CODE rapid ionosphere product (1 day) complemented with ionosphere predictions (2 days)
`COD.EPH_5D`	Last update of CODE 5–day orbit predictions, from rapid analysis, including all active GPS and GLONASS satellites
`CODwwwwd.EPH_U`	CODE ultra-rapid GNSS orbits from the 24UT solution available until the corresponding early rapid orbit is available (to ensure a complete coverage of orbits even if the early rapid solution is delayed after the first ultra-rapid solutions of the day)
`CODwwwwd.ERP_U`	CODE ultra-rapid ERPs belonging to the ultra-rapid orbits

CODE *MGEX* products available at `ftp://ftp.aiub.unibe.ch/CODE_MGEX/CODE`

`yyyy/COMwwwwd.EPH.Z`	CODE MGEX final GNSS orbits for GPS, GLONASS, Galileo, BeiDou, and QZSS satellites, SP3 format
`yyyy/COMwwwwd.ERP.Z`	CODE MGEX final ERPs belonging to the MGEX final orbits
`yyyy/COMwwwwd.CLK.Z`	CODE MGEX final clock product consistent to the MGEX final orbits, clock RINEX format, with a sampling of 30 sec for the GNSS satellite and reference (station) clock corrections and 5 minutes for all other station clock corrections
`yyyy/COMwwwwd.BIA.Z`	GNSS code biases related to the MGEX final clock correction product, bias SINEX format v1.00
`yyyy/COMwwwwd.DCB.Z`	GNSS code biases related to the MGEX final clock correction product, Bernese format

Since GPS week 1706, CODE is generating a pure one–day solution (label “COF”) in addition to the traditional three–day long–arc solution (label “COD”) for the IGS final product series. The result files from both series are submitted to the IGS data centers hosting the products. The related files are listed in Table 2.

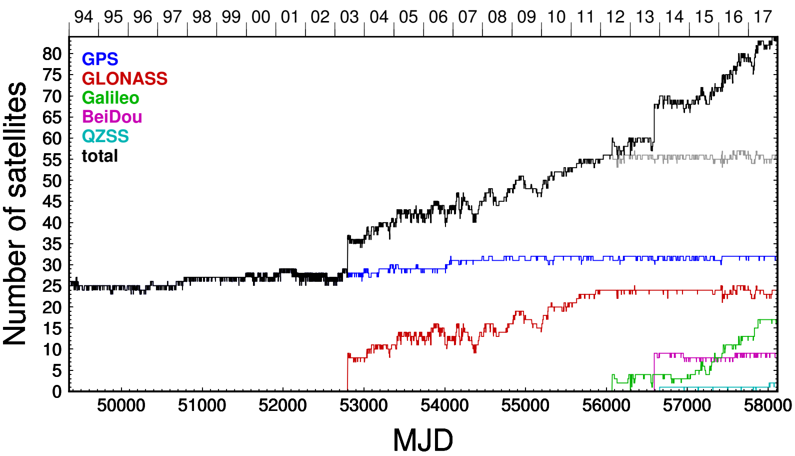

Figure 1: Development of the number of satellites in the CODE orbit products.

Table 2: CODE final products available in the product areas of the IGS data centers.

Files generated from three–day long–arc solutions:	
CODwwwwd.EPH.Z	GNSS ephemeris/clock data in daily files at 15–min intervals in SP3 format, including accuracy codes computed from a long–arc analysis
CODwwwwd.SNX.Z	GNSS daily coordinates/ERP/GCC from the long–arc solution in SINEX format
CODwwwwd.CLK.Z	GPS satellite and receiver clock corrections at 30–sec intervals referring to the COD–orbits from the long–arc analysis in clock RINEX format
CODwwwwd.CLK_05S.Z	GPS satellite and receiver clock corrections at 5–sec intervals referring to the COD–orbits from the long–arc analysis in clock RINEX format
CODwwwwd.TRO.Z	GNSS 2–hour troposphere delay estimates obtained from the long–arc solution in troposphere SINEX format
CODwwww7.ERP.Z	GNSS ERP (pole, UT1−UTC) solution, collection of the 7 daily COD–ERP solutions of the week in IGS IERS ERP format
CODwwww7.SUM	Analysis summary for 1 week
Note, that the COD–series is identical with the files posted at the CODE's aftp server, see Table 1.	
Files generated from pure one–day solutions:	
COFwwwwd.EPH.Z	GNSS ephemeris/clock data in daily files at 15–min intervals in SP3 format, including accuracy codes computed from a pure one–day solution
COFwwwwd.SNX.Z	GNSS daily coordinates/ERP/GCC from the pure one–day solution in SINEX format
COFwwwwd.CLK.Z	GPS satellite and receiver clock corrections at 30–sec intervals referring to the COF–orbits from the pure one–day analysis in clock RINEX format
COFwwwwd.CLK_05S.Z	GPS satellite and receiver clock corrections at 5–sec intervals referring to the COF–orbits from the pure one–day analysis in clock RINEX format
COFwwwwd.TRO.Z	GNSS 2–hour troposphere delay estimates obtained from the pure one–day solution in troposphere SINEX format
COFwwww7.ERP.Z	GNSS ERP (pole, UT1−UTC) solution, collection of the 7 daily COF–ERP solutions of the week in IGS IERS ERP format
COFwwww7.SUM	Analysis summary for 1 week

Other product files (not available at all data centers):	
CODGddd0.yyI.Z	GNSS hourly global ionosphere maps in IONEX format, including satellite and receiver P1−P2 code bias values
CKMGddd0.yyI.Z	GNSS daily Klobuchar-style ionospheric (alpha and beta) coefficients in IONEX format
GPSGddd0.yyI.Z	Klobuchar-style ionospheric (alpha and beta) coefficients from GPS navigation messages represented in IONEX format

The development of the included satellite systems in the CODE solution is illustrated in Figure 1. Since May 2003 CODE is generating all its products for the IGS legacy series based on a combined GPS and GLONASS solution. The network used by CODE for the final processing is shown in Figure 2. Almost 80% of the stations support GLONASS (red stars).

Since the beginning of MGEX in 2012 CODE is contributing. With the beginning of 2014 CODE's contribution to IGS MGEX is a five-system solution considering GPS, GLONASS, Gelileo, BeiDou, and QZSS. Meanwhile it is included in the operational processing and is published with the same schedule as the final product series. It includeed up to 84 satellites by the end of year 2017.

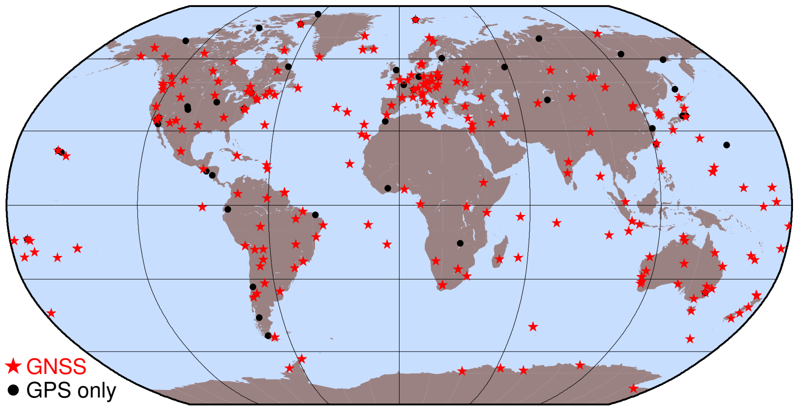

Figure 2: Network used for the GNSS final processing at CODE by the end of 2017.

Referencing of the products

The products from CODE have been registered and should be referenced as:

- Dach, Rolf; Schaer, Stefan; Arnold, Daniel; Prange, Lars; Sidorov, Dmitry; Sušnik, Andreja; Villiger, Arturo; Jäggi, Adrian (2016). *CODE ultra-rapid product series for the IGS*. Published by Astronomical Institut, University of Bern. URL: http://www.aiub.unibe.ch/download/CODE; DOI: 10.7892/boris.75676.1 .
- Dach, Rolf; Schaer, Stefan; Arnold, Daniel; Prange, Lars; Sidorov, Dmitry; Sušnik, Andreja; Villiger, Arturo; Jäggi, Adrian (2016). *CODE rapid product series for the IGS*. Published by Astronomical Institut, University of Bern. URL: http://www.aiub.unibe.ch/download/CODE; DOI: 10.7892/boris.75854.1 .
- Dach, Rolf; Schaer, Stefan; Arnold, Daniel; Prange, Lars; Sidorov, Dmitry; Sušnik, Andreja; Villiger, Arturo; Jäggi, Adrian (2016). *CODE final product series for the IGS*. Published by Astronomical Institut, University of Bern. URL: http://www.aiub.unibe.ch/download/CODE; DOI: 10.7892/boris.75876.2 .
- Prange, Lars; Sušnik, Andreja; Arnold, Daniel; Dach, Rolf; Schaer, Stefan; Sidorov, Dmitry; Villiger, Arturo; Jäggi, Adrian (2017). *CODE product series for the IGS MGEX project*. Published by Astronomical Institute, University of Bern. URL: http://www.aiub.unibe.ch/download/CODE_MGEX; DOI: 10.7892/boris.75882.1 .
- Steigenberger, Peter; Lutz, Simon; Dach, Rolf; Schaer, Stefan; Jäggi, Adrian (2014). CODE repro2 product series for the IGS. Published by Astronomical Institut, University of Bern. URL: http://www.aiub.unibe.ch/download/REPRO_2013; DOI: 10.7892/boris.75680 .

3 Changes in the daily processing for the IGS

The CODE processing scheme for daily IGS analyses is constantly subject to updates and improvements. The last technical report was published in Dach et al. (2017).

In Section 3.1 we give an overview of important development steps in the year 2017. Section 3.2 describes the advancing of the procedure to generate the final clock product at CODE. The progress in the MGEX product chain is detailed in a dedicated Section 4.

3.1 Overview of changes in the processing scheme in 2017

Table 3 gives an overview of the major changes implemented during year 2017. Details on the analysis strategy can be found in the IGS analysis questionnaire at the IGS Central Bureau (`ftp://ftp.igs.org/pub/center/analysis/code.acn`).

Several other improvements not listed in Table 3 were implemented, too. Those mainly concern data download and management, sophistication of CODE's analysis strategy, software changes (improvements), and many more. As these changes are virtually not relevant for users of CODE products, they will not be detailed on any further.

Use of RINEX 3 data in the IGS final product generation

Since end of January 2017, CODE is using also RINEX 3 files to generate the IGS final products. A statistics on the number of RINEX files from different types is shown in Figure 3. No RINEX file from streams or unknown source are considered. During the year the number of available RINEX 3 files for the stations included in the CODE final processing did increase from about 40% to nearly 50%.

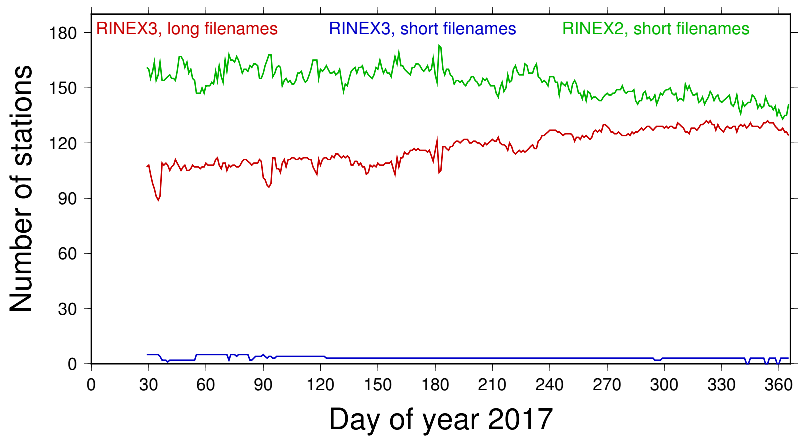

Figure 3: Usage of RINEX observations files for CODE final processing.

Table 3: Selected modifications of the CODE processing over 2017.

Date	DoY/Year	Description
24-Jan-2017	024/2017	Start to write .BIA files according to finalized Bias-SINEX format version 1.00
30-Jan-2017	029/2017	Switch from IGb08 to IGS14 for PCV and coordinates At the same time further changes have been activated: • Extent the list of stations in the final processing by additional GPS/GLONASS stations in remote areas • Enable the new scheme of clock final product generation including GPS and GLONASS (see Section 3.2 for more details) • Extent the use of RINEX 3 files to the final processing according to the priority list: 1. RINEX 3 files with long names generated in the receiver 2. RINEX 3 files with short names 3. RINEX 2 files 4. RINEX 3 files with long names generated from a stream 5. RINEX 3 files from unknown sources The usage of the files is reported in the weekly summary (see also Figure 3).
22-Mar-2017	081/2017	The legacy and MGEX solutions are running consistently on the same software version and configuration files.
12-May-2017	132/2017	SLR observation validation considers now also the MGEX solution (e.g., the validation is extended to Galileo, BeiDou, and QZSS satellites).
13-Jun-2017	164/2017	Bias combination over 30 days established for MGEX results back to week 1934. Wide-lane/narrow-lane ambiguity resolution activated in MGEX solution for all systems (apart from GLONASS) using these 30-day bias values.
19-Jun-2017	170/2017	Single frequency data indicated by with lower case for the system identifier in the RINEX statistics at `ftp://ftp.aiub.unibe.ch/igsdata` and `ftp://ftp.aiub.unibe.ch/mgex` .
03-Aug-2017	215/2017	Reschedule the generation of the final rapid solution (see Section 3.3 in Dach et al. 2015b, for a description of the procedure)
06-Aug-2017	218/2017	Complete update of the ocean tidal loading table based on FES2004
14-Aug-2017	226/2017	Several improvements on the MGEX solution: • Activate the usage of published meta-data for Galileo IOV satellites and the QZSS-1 satellite (attitude modelling, albedo based on the available satellite properties). • Use pulses with a 12 hour sampling for Galileo satellites. • Sampling in the published precise orbit file was increased from 15 to 5 minutes.
13-Aug-2017	225/2017	Improve the MGEX clock generation (the regionally available systems BeiDou and QZSS cannot harm the other, global systems anymore). Densify the satellite clocks from 5 minutes to 30 seconds.
22-Aug-2017	234/2017	Publish the results from EGSIEM reprocessing at `ftp://ftp.aiub.unibe.ch/REPRO_2015` after changing the server. A list of the available files in given in Table 4 whereas the reprocessing itself was already described in Dach et al. (2016).
05-Nov-2017	309/2017	Enable the use of the published meta-data for Galileo-FOC and QZS-2 satellites (related to attitude and albedo modelling) in the MGEX solution.
18-Dec-2017	335-348	Due to changes in the software wrong antenna trust values have been used during two weeks for Galileo IOV and QZSS satellites (in the MGEX solution) and for GPS satellite G25 (in both, the IGS final and MGEX solutions)

New FTP server, publishing of prodcuts from EGSIEM reprocessing

For different reasons we had to change the URL to our FTP server. To access the products from CODE directly you have now to use the new URL `ftp://ftp.aiub.unibe.ch/CODE` (instead of ftp://ftp.unibe.ch/aiub/CODE).

An advantage is that this change of the URL was related to an update of the hardware that did allow us to put the results from the most recent reprocessing online in August 2017. The reprocessing has been carried out at AIUB in the frame of the European Gravity Service for Improved Emergency Management (EGSIEM) project during the years 2015 and 2016. It contains the following series of products:

	GPS	GLONASS
GNSS satellite orbits:	since 1994	since 2002
GNSS satellite clock corrections:		
sampling 30 s:	since 2000	since 2008
sampling 5 s:	since 2003	since 2010

The list of product files is provided in Table 4 .

The usage of these data shall be referenced by:

- Sušnik, Andreja; Dach, Rolf; Maier, Andrea, Arnold, Daniel; Schaer, Stefan; Jäggi, Adrian (2014). CODE reprocessing series in the frame of EGSIEM. Published by Astronomical Institut, University of Bern. URL: `http://www.aiub.unibe.ch/download/REPRO_2015`; DOI: 10.7892/boris.80011 .

A detailed description of the processing scheme was already given in Dach et al. (2016) .

Table 4: Products from EGSIEM reprocessing available at ftp://ftp.aiub.unibe.ch/REPRO_2015/CODE/yyyy/

`yyyy/CODwwwwd.EPH.Z`	GPS and GLONASS orbits in SP3 format
`yyyy/CODwwwwd.ERP.Z`	ERPs belonging to the orbits in IGS format
`yyyy/CODwwwwd.CLK.Z`	Clock product in clock RINEX format, with a sampling of 30 sec for the GPS&GLONASS satellite and reference (station) clock corrections and 5 minutes for all other station clock corrections
`yyyy/CODwwwwd.CLK_05S.Z`	Clock product in clock RINEX format, with a sampling of 5 sec for the GPS&GLONASS satellite and reference (station) clock corrections and 5 minutes for all other station clock corrections
`yyyy/CODwwwwd.SNX.Z`	Daily solution in SINEX format containing parameters for station coordinate, ERP, geocenter coordinates, and satellite antenna offsets (Z-component)
`yyyy/CODwwwwd.TRO.Z`	Troposphere product in troposphere SINEX format
`yyyy/CODwwww7.SNX.Z`	Weekly solution in SINEX format (sme parameters as the daily files)
`yyyy/CODwwww7.ERP.Z`	Collection of the 7 daily CODE-ERP solutions of the week
`yyyy/CODwwww7.SUM.Z`	Summary file

3.2 Advancing the final clock product generation at CODE

Since 2015 CODE contributes a combined GPS and GLONASS clock product to the IGS rapid combination. This includes phase-based densification of the estimated 5 minute clocks to a 30 second clock product. The final clock product remained a GPS only solution with an additional densification step using 1 s RINEX data to produce 5 s clock products. In a first step, our final clock procedure was adapted for a reprocessing (repro15) within the framework of the European Gravity Service for Improved Emergency Management (EGSIEM). This included the reprocessing a consistent reprocessing of GPS and GLONASS orbits and clock from 1994 up to 2016. The clock estimation was produced using up to 150 stations. The clock were estimated by dividing the network into three clusters and solve them independently. Afterwards, the final clock product was generated by combining the clock results of all three clusters on the RINEX clock level. The routine already included the production of not only 30 s, but also a combined GPS / GLONASS 5 s clock product.

After the reprocessing effort CODE decided to include GLONASS also into the operational final clock estimation. With the switch from the old ITRF2008 to the new ITRF2014 reference frame, not only the reference frame was changed, but also the old IGS final clock estimation scheme was revised. The adapted processing scheme for the final clock solution is shown in Fig. 4. Instead of following our traditional clustering approach, we redesigned our clock estimation to combine the individual contributions on the normal equation level instead of combining the individual clock solutions. The new processing scheme starts with observation data which were screened using a precise-point positioning approach. Additionally, during the PPP screening procedure, the necessary code biases are already estimated and available for the final clock estimation.

The major change between the old and the new scheme is that each station is individually processed with pre-eliminated receiver clocks to obtain station-wise NEQ's. After stacking the station-wise NEQ's leading to the full set of satellite clocks a procedure of various pre-elimination steps is introduced to reduce the needed time for the inversion of the whole system. Two steps of pre-eliminating creating first two NEQ's with each a half days and then four NEQ's with each a quarter of the day which contain 6 hours of satellite clocks each. The four 6-hours NEQ's are solved and the satellite clocks combined to create the complete one day clock product. The outcome is identically as if the whole system would be solved in one step, but due to the pre-elimination step the process could be speed up by running the tasks in parallelized.

The station clocks are afterwards estimated station-wise introducing the previously determined satellite clocks which can be again run in parallel. The 5 min clocks are then, as it was done in the old processing scheme, densified twice using a phase-base interpolation creating 30 s clocks (using all stations for the interpolation) and 5 s clocks (using more than 100 stations providing high-rate 1s data).

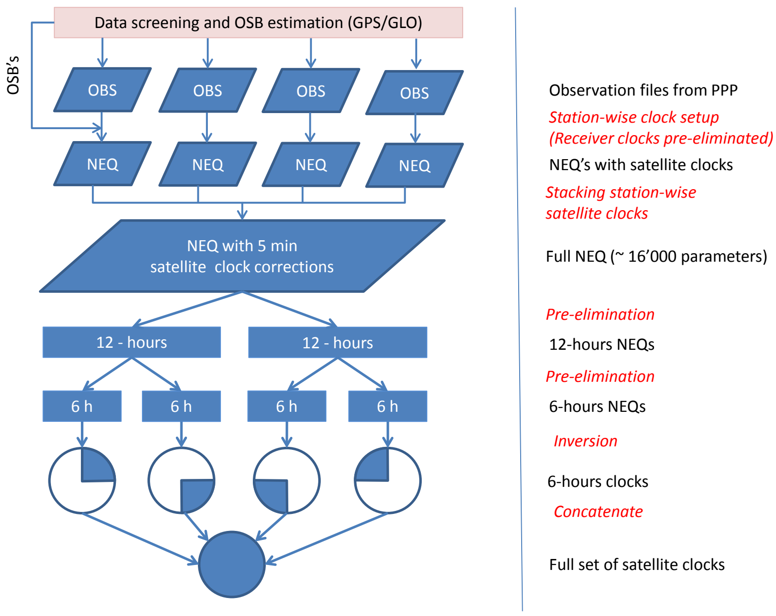

Figure 4: Processing scheme of the IGS final clock product.

4 CODE contribution to the IGS–MGEX campaign

CODE contributes to the IGS Multi-GNSS EXtension (MGEX) with an orbit and clock solution since 2012 (Prange et al. 2016). In the course of the current reporting season we have come one step closer to MGEX' goal to integrate new GNSS (namely Galileo, BDS, QZSS) into existing IGS-related processing chains by migrating our MGEX effort from a development environment into CODE's operational environment used for generating the IGS products. This change comprises the merge of data-, user-, and software-environments. Since many of the recent developments concerning aspects such as modelling (e.g., attitude, SRP, albedo, antenna thrust, antenna calibrations) and data handling (e.g., RINEX3 data format, merge of RINEX data archives) are somehow driven by or related to the emerge of new GNSS, we expect to see synergy effects w.r.t. data analysis, organization (e.g., non-redundant meta-data handling) and software development. One example is the integration with the recently revised handling of observation types and code biases (Villiger et al. 2017a) - an improvement that effects multi-GNSS analysis far more than a GPS-only analysis. Moreover we expect improvements concerning the availability and quality of our MGEX products (more manpower) and efficient use of computing resources (common data pool) at CODE AC.

Another focus was on improving the background models for the new GNSS. In late 2016 the European Global Navigation Satellite Systems Agency (GSA) published meta-data of the Galileo IOV spacecraft (www.gsc-europa.eu) followed later by a corresponding release concerning the the FOC satellites. The Cabinet Office of the Japanese Government (http://qzss.go.jp) started to provide information of the QZSS satellites in mid 2017. With these information it has become possible to assess the impact of correct meta data on GNSS analysis products. The impact of the Galileo transmit antenna calibrations on station coordinates was studied by (Villiger et al. 2017b). The disclosure of the satellite mass, size, surface properties, and antenna thrust enabled us to implement background models for the transmit antenna thrust and Earth re-radiation (see (Prange et al. 2017a) and (Prange et al. 2017b)). By activating these models the SLR offset of Galileo and QZSS orbits could be significantly reduced (Fig. 5). Furthermore we implemented the attitude laws for Galileo IOV and FOC spacecraft based on the desclosed information.

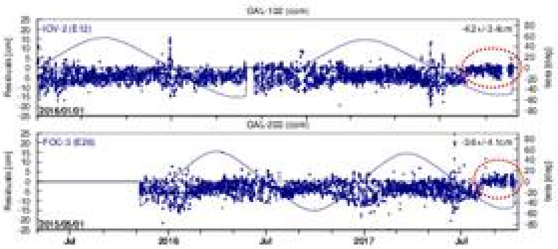

Figure 5: SLR residuals of Galileo orbits from CODE's MGEX solution. The validation is provided by the IGS MGEX (http://mgex.igs.org). Time periods with activated albedo and antenna thrust models are encircled with red dots.

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NRCan Analysis Center Technical Report 2017

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1 Introduction

This report covers the major activities conducted at the NRCan Analysis Center (NRCan-AC) and product changes during the year 2017 (products labelled "`em*`"). Additionally, changes to the stations operated by NRCan are briefly described. Readers are referred to the Analysis Coordinator web site at http://acc.igs.org for historical combination statistics of the NRCan-AC products.

2 NRCan Core Products

The Final GPS products continued to be estimated with JPL's GIPSY-OASIS software in 2017, with no major changes to the processing strategy.

The Rapid and Ultra-Rapid products continued to be generated using the Bernese software version 5.2 (Dach et al. 2015).

An improved strategy for a priori station coordinates selection for the Ultra, Rapid and Final GPS+GLONASS products was implemented. It generates station coordinates statistics from the following list of solutions to detect potential station displacement following known or unknown events such as earthquakes, a receiver/antenna changes or other:

1. IGS14 original cumulative solution;
2. IGS14 weekly cumulative solutions;
3. ITRF-2014 original cumulative solution;

4. IGS14 independent weekly solutions;
5. Real-time in-house PPP solutions.

All available station position solutions are averaged and a discrepancy check is performed. When all solutions agree with the average within a pre-determined threshold, the a priori station coordinates are taken from the first available solution listed above with its associated uncertainty. For stations exceeding threshold, the average position will be used with a proper uncertainty assigned, and a message is issued to the operator for further evaluation and review. Stations can also be rejected, on the fly, if the discrepancy is too high.

All NRCan orbits and clock products were switched to IGS14 (see IGS Mail #7399) on GPS week 1934 (2017, January 29).

The products available from the NRCan-AC are summarized in Table 1. The Final and Rapid products are available from the following anonymous ftp site: `ftp://rtopsdata1.geod.nrcan.gc.ca/gps/products`.

3 Ionosphere and DCB monitoring

Daily and near-real-time ionosphere products and DCB estimates continued to be generated internally. NRCan's global ionosphere maps at 1 hour intervals (`emrg[ddd]0.[yy]i`) which includes GPS and GLONASS DCBs continued to be available at CDDIS with a latency of less than 2 days. In addition to GPS, starting in 2017 ionospheric irregularities as sensed by GLONASS phase rate derived indices from real-time IGS network are also monitored in near-real-time and archived for long-term analysis. Advantages of additional constellation in monitoring small spatiotemporal scale ionospheric irregularities have been presented (Ghoddousi-Fard 2017a, b). The impact of different receiver types present in real-time IGS network and satellite constellations on GNSS-derived ionospheric indices were studied (Ghoddousi-Fard 2017c).

4 Operational NRCan stations

In addition to routinely generating all core IGS products, NRCan is also providing public access to GPS/GNSS data for more than 100 Canadian stations. This includes 38 stations currently contributing to the IGS network through the Canadian Geodetic Survey's Canadian Active Control System (CGS-CACS), the CGS Regional Active Control System (CGS-RACS), and the Geological Survey of Canada's Western Canada Deformation Array (GSC-WCDA). The NRCan contribution to the IGS network includes 26 GNSS plus 12 GPS only stations. Since December 7, 2016, NRCan has been contributing RINEX v3.03 data for 30 GNSS stations from the CGS-CACS network. Several upgrades/changes to

Table 1: NRCan-AC products.

Product	Description
Repro2:	

`em2wwwwd.sp3`
`em2wwwwd.clk`
`em2wwwwd.snx`
`em2wwww7.erp`
	GPS only
	• Time Span 1994-Nov-02 to 2014-Mar-29
	• Use of JPL's GIPSY-OASIS II v6.3
	• Daily orbits, ERP and SINEX
	• 5-min clocks
	• Submission for IGS repro2 combination

Final (weekly):	

`emrwwwwd.sp3`
`emrwwwwd.clk`
`emrwwwwd.snx`
`emrwwww7.erp`
`emrwwww7.sum`
	GPS only
	• Since 1994 and ongoing
	• Use of JPL's GIPSY-OASIS II v6.4 from 2016-Feb-01
	• Daily orbits, ERP and SINEX
	• 30-sec clocks
	• Weekly submission for IGS Final combination

	GPS+GLONASS • Since 2011-Sep-11 and ongoing • Use of Bernese 5.0 until 2015-Jan-31 • Use of Bernese 5.2 since 2015-Feb-01 • Daily orbits and ERP • 30-sec clocks • Weekly submission for IGLOS Final combination • Station XYZ are constrained, similar to our Rapid solutions
Rapid (daily):	

`emrwwwwd.sp3`
`emrwwwwd.clk`
`emrwwwwd.erp`
	GPS only
	• From July 1996 to 2011-05-21
	• Use of JPL's GIPSY-OASIS (various versions)
	• Orbits, 5-min clocks and ERP (30-sec clocks from 2006-Aug-27)
	• Daily submission for IGR combination

	GPS+GLONASS • Since 2011-Sep-06 and ongoing • Use of Bernese 5.0 until 2015-Feb-11 • Use of Bernese 5.2 from 2015-Feb-12 • Daily orbits and ERP • 30-sec GNSS clocks

Table 1: NRCan-AC products (continued).

Product	Description
Ultra-Rapid (hourly):	

`emuwwwwd_hh.sp3`
`emuwwwwd_hh.clk`
`emuwwwwd_hh.erp`
	GPS only
	• From early 2000 to 2013-09-13, hour 06
	• Use of Bernese 5.0
	• Orbits, 30-sec clocks and ERP (hourly)
	• Submission for IGU combination (4 times daily)

	GPS+GLONASS • Since 2013-09-13, hour 12 • Use of Bernese 5.0 until 2015-Feb-12 • Use of Bernese 5.2 since 2015-Feb-13 • Orbits and ERP (hourly) • 30-sec GNSS clocks (every 3 hours) • 30-sec GPS-only clocks (every other hours) • Submission for IGU/IGV combination (4 times daily)
Real-Time:	

	GPS only
	• Since 2011-11-10
	• In-house software (HPGPS.C)
	• RTCM messages:
	  – orbits and clocks:1060 (at Antenna Reference Point)
	  – pseudorange biases: 1059
	• Interval: 5 sec

the CGS-CACS were completed in 2017 and these are listed in Table 2. Figure 1 shows a map of the NRCan GPS/GNSS network as of January 2018. Further details about NRCan stations and access to NRCan public GPS/GNSS data and site logs can be found at `https://webapp.geod.nrcan.gc.ca/geod/data-donnees/cacs-scca.php` or from the following anonymous ftp site: `ftp://rtopsdata1.geod.nrcan.gc.ca/gps/` .

5 Acknowledgement

ESS Contribution number / Numéro de contribution du SST: 20170334

Table 2: NRCan Station Upgrades in 2017.

Station	Date	Remarks
dra3	2017-12-13	Station receiver upgraded to TPS NET-G5
dra4	2017-12-13	Station receiver upgraded to TPS NET-G5
dubo	2017-02-23	Station receiver switched to SEPT POLARX5
picl	2017-02-24	Station receiver switched to SEPT POLARX5 and antenna changed to TPSCR.G3 NONE
prd2	2017-12-11	Station receiver upgraded to TPS NET-G5
prd3	2017-12-11	Station receiver upgraded to TPS NET-G5
stjo	2017-09-29	New antenna cable
stj2	2017-09-29	New antenna cable
stj3	2017-09-29	New antenna cable
vald	2017-06-07	New antenna cable
winn	2017-02-23	Station receiver upgraded to TPS NET-G3A
winn	2017-12-05	Station receiver upgraded to TPS NET-G5
yel3	2017-01-26	Antenna changed to TWIVP6050_CONE NONE

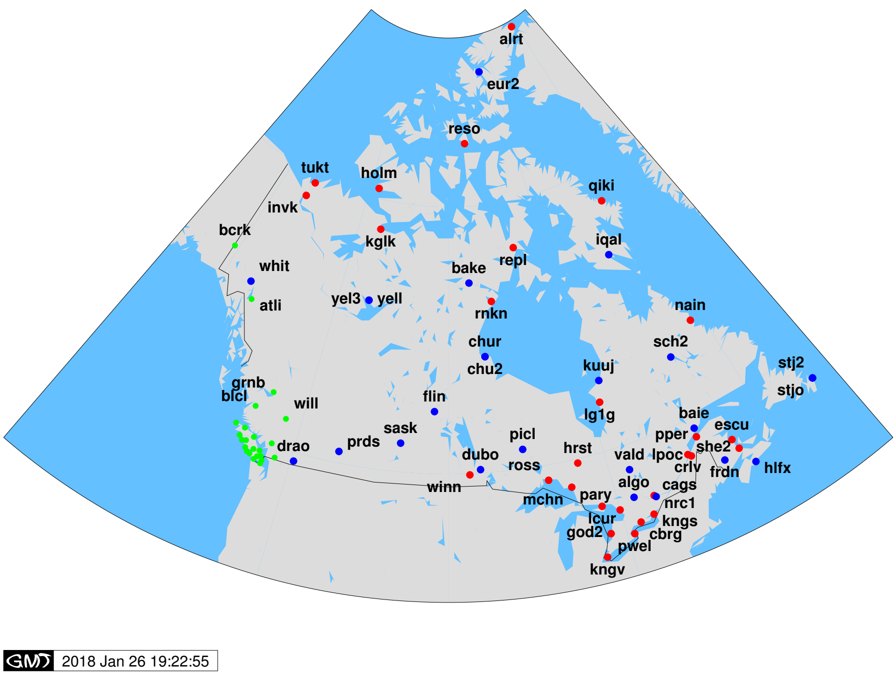

Figure 1: NRCan Public GPS/GNSS Stations (CGS-CACS in blue, CGS-RACS in red and GSC-WCDA in green).

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The ESA/ESOC IGS Analysis Centre

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1 Introduction

The IGS Analysis Centre of the European Space Agency (ESA) is located at the European Space Operations Centre (ESOC) in Darmstadt, Germany. The ESA/ESOC Analysis Centre has been involved in the IGS since its very beginning in 1992. In this report we give a summary of the IGS related activities at ESOC in 2017.

2 Overview

2.1 Routine Products

The ESA/ESOC IGS Analysis centre contributes to all the core IGS analysis centre products, being:

- Final GNSS (GPS+GLONASS) products
  - Provided weekly, normally on Friday after the end of the observation week
  - Based on 24hour solutions using 150 stations
  - True GNSS solutions obtained by simultaneously and fully consistently processing of GPS and GLONASS measurements, using a total of around 55 GNSS satellites
  - Consisting of Orbits, Clocks (30s), daily SINEX with station coordinates and EOPs, and Global Ionosphere Maps
- Rapid GNSS (GPS+GLONASS) products
  - Provided daily for the previous day

  - Available within 3 hours after the end of the observation day
  - Based on 24hour solutions using 110 stations
  - True GNSS solutions obtained by simultaneously and fully consistently processing of GPS and GLONASS measurements, using a total of around 55 GNSS satellites
  - Consisting of Orbits, Clocks, EOPs, and hourly and 2-hourly ionosphere maps and ionosphere predictions
  - Rapid SINEX with station coordinates and EOPs available as well
- Ultra-Rapid GNSS (GPS+GLONASS) products
  - Provided 4 times per day covering a 48 hour interval; 24 hours of estimated plus 24 hours of predicted products
  - Available within 3 hours after the end of the observation interval which ending at 0, 6, 12, and 18 hours UTC
  - Based on 24 hours of observations using 110 stations
  - True GNSS solutions obtained by simultaneously and fully consistently processing of GPS and GLONASS measurements, using a total of around 55 GNSS satellites
  - Consisting out of Orbits, Clocks, and EOPs
- Real-Time GNSS services
  - Generation of two independent real-time solution streams
  - Analysis Centre Coordination
  - Generation and dissemination of the IGS Real Time Combined product stream
- GNSS Sensor Stations
  - A set of 10 globally distributed GNSS sensor stations
  - Station data available in real-time with 1 second data sampling

Besides these core products ESA is very active in different working groups, e.g., the Real-Time Service where besides being one of the analysis centres we are also responsible for the analysis centre coordination, infrastructure commission (working group chair), MGEX, antenna calibarations, and satellite orbit modeling working groups.

An up to date description of the ESA IGS Analysis strategy may always be found at: http://navigation-office.esa.int/products/gnss-products/esa.acn

2.2 Product Changes

The main changes in our processing in 2017 were the following:

- Switch to new NAPEOS version 4.0 (November 2016)
- Switch to ITRF2014 including PSD functions (done on GPSweek 1934)
- Improvements the GNSS box-wing models
  - Include Power Thrust for GPS and GLONASS
  - Correct Infrared (IR) properties in our box-wing models (GPSweek 1935)
  - Box-wing for IIF turned back on, was turned off in 2016, after tuning some of the material properties
  - But still investigating the IIF satellite performance (on-going)

2.3 Product Highlights

The main highlight of the ESA/ESOC Analysis Centre products is that they are one of the best products available from the individual IGS analysis centres. Furthermore, the ESA products are one of the most complete GNSS products. In fact ESA/ESOC was the first IGS analysis centre to provide a consistent set of GNSS orbit *and* clock products. Our GNSS products constituted the very first products that could, and are, used for true GNSS precise point positioning. In particular for this purpose, the sampling rate of our final GPS+GLONASS clock products is 30 seconds. Another special feature of the ESA products is that they are based on completely independent 24 hour solutions. Although this does not necessarily lead to the best products, as in the real world the orbits and EOPs are continuous, it does provide a very interesting set of products for scientific investigations as there is no aliasing and no smoothing between subsequent solutions. An other unique feature is that our rapid products are, besides being one of the best, also one of the most timely available products. Normally our GNSS rapid products are available within 2 hours after the end of the observation day whereas the official GPS-only IGS products become available only 17 hours after the end of the observation day, a very significant difference. Another important feature of the ESA products is that we use a box-wing model for the GNSS satellites to a priori model the Solar- and Earth Albedo radiation pressure. The GNSS block type specific models were tested thoroughly in the scope of our IGS reprocessing and the results were presented at the IGS workshop citeSpringer2014. Significant improvements were observed for most, if not all, estimated parameters. Last but not least it is wortwhile to mention that besides being an analysis center in the IGS ESA/ESOC is also an analysis center in the IDS and the ILRS. This represents a rather unique achievement in that one single software version, NAPEOS Springer (2009), contributes to the products and solutions of three different space geodetic techniques.

Work is in progress to also add VLBI to our processing capabilities.

3 GNSS Sensor Station Upgrade

ESA/ESOC continues to provide worldwide data for all GNSS constellations to the IGS via its 10 public stations, and to expand ESA's GNSS OBSERVATION NETWORK (EGON). This expansion is accomplished by focusing on the establishment of collaborations with third parties to install new stations at various locations around the world such as in South Africa, Brasil, Russia, Canada, etc. EGON is also present at all ESA Deep Space sites and other locations where ESA have satellite tracking assets around the world (see map below).

The entire EGON network now operates Septentrio PolarRx4 receivers with SEPCHOKE antennas, with the exception of MGUE, MAL2, MAS1 and FAA1 where the Leica AR25.R4 antennas are installed. The station network has been expanded in recent times with installations in Awarua (New Zealand), Dubai (U.A.E), Malaysia, Tsukuba (Japan), Bishkek (Kyrgyzstan), Darmstadt (Germany) and Hartebeesthoek (South Africa) and plans are on-going for up to 9 more stations in the next 18 months. No data is publicly available for the time being for any of the newly installed stations. The Septentrio PolaRX4 receivers have proven to be very capable at our stations and they provide all phase and pseudo-range measurements for the GNSS constellations as available: GPS, GLONASS, Galileo, QZSS, Compass, SBAS, EGNOS, etc, last year ESA/ESOC has started contributing with long name daily, hourly and high-rate multi- GNSS RINEX 3 data to the IGS for the 10 ESA/ESOC public stations. ESA/ESOC continues to provide the NBS (NavBits) data from GPS L1 in support of LEO Precise Orbit Determination for EUMETSAT.

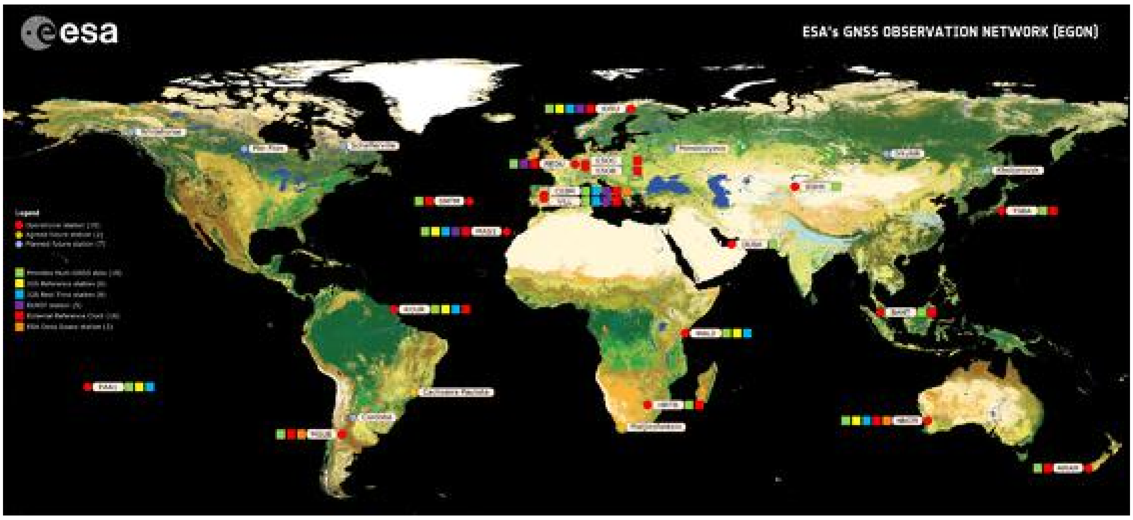

Figure 1: ESA/ESOC GNSS Station Network

For 2018/2019 worldwide coverage is planned to be enhanced considerably with negotiations with third parties in Brasil, South Africa, Argentina, Russia and Canada ongoing. The station map shows a projection of the impact on the global coverage for the inclu- sion of the 9 planned future ESA/ESOC stations, enhancing worldwide GNSS satellite coverage, aiming to provide full triple station coverage for al GNSS satellites at all times.

http://navigation-office.esa.int/ESA's_GNSS_Observation_Network_(EGON).html

4 Ionosphere Modeling Activities

ESA/ESOC contributes with IONEX products to the IGS Ionosphere Working Group since its inception in 1998. Up to now, ionosphere products for the IGS are still based on a single-layer approach, where the vertical TEC is represented by spherical harmonics, in combination with an estimation of daily receiver and satellite DCBs. ESA IONEX files are delivered in final (2h time resolution) and in rapid (2h and 1h time resolution) mode to the IGS, and they are based on processing both GPS and GLONASS observations. In addition, predicted products are delivered. ESOC employs the Ionosphere Monitoring Facility (IONMON) for its ionosphere processing, which in 2013 became and integral part of ESOCâĂŹs NAPEOS software.

5 GNSS Research Activities

5.1 Multi-GNSS Research

We frequently process and reprocess the data from the IGS Multi-GNSS Experiment (MGEX) as at the current stage we prefer a detailed analysis of the MGEX data over routine analysis. In the scope of these activities we have derived a consistent set of Galileo, BeiDou and QZSS PCO/PCVs based on processing the data of 2014 to 2017. We have extended our box-wing modeling activities now also to the satellites of the âĂIJnewâĂİ constellations, i.e., Galileo, BeiDou and QZSS. We believe that for BeiDou and QZSS an accurate model of the satellites will be of great benefit, if not even mandatory. This is due to the fact that for small beta angles these satellites switch their attitude mode from yaw-steering (the nominal attitude mode used by GPS, GLONASS and Galileo) to orbit normal mode. In the orbit normal mode the satellite are no longer oriented towards the Sun and thus the solar radiation pressure becomes very hard to model. In the orbit normal mode phase the widely used ECOM model, and also the enhanced ECOM2 model, fail to properly model the radiation forces. Also for the two eccentric Galileo satellites a dedicated model has noticable advantages over ECOM2.

The main interesting features and challenges we have found so far in our multi-GNSS analysis activities were presented at different meetings like the EGU, AGU, and most prominently at the IGS workshops in 2014, 2016 and 2017, and may be summarized as:

- Severe inconsistency between the three GPS phase signals (L1, L2, and L5); a periodic effect with an amplitude of 50 mm clearly visible
- Severe challenges to model the BeiDou GEO satellite due to orbit normal mode attitude and poor tracking geometry, the latter unfortunately unavoidable for GEOs.
- Severe challenges to model the QZSS satellite during the orbit normal mode phase ($|\beta| < 20^0$), fortunately the latest QZSS satellites are using the yaw-attitude steering as used by most GNSS satelllites
- Significant challenges to model the BeiDou MEO and IGSO satellites during the orbit normal mode phase ($|\beta| < 4^0$), but fortunately the latest BeiDou satellites are using the yaw-attitude steering as used by most GNSS satelllites
- Strong elevation dependent pattern in the BeiDou pseudo range residuals for the MEO satellites that needs to be corrected, in particular if one wants to used Melbourne–Wübbena based integer ambiguity resolution although the latest satellites do no longer seem to *suffer* from this (d)effect
- Strong azimuthal dependent pattern in the Galileo carrier phase residuals, clearly an azimuthal ANTEX pattern needed, now covered by the release of the Galileo metadata
- Due to larger size and/or lower weight the radiation pressure effects on the latest GNSS satellites (GPS IIF, GLONASS K, Galileo, BeiDou and QZSS) is much more pronounced then on the early GPS and GLONASS satellites. Consequently much more effort has to be put into the accurate modeling of *all* new GNSS satellites

In 2017 our prime focus has been to improve our understanding and modelling of the Galileo satellites to such a level that they can be included in our core IGS products (final, rapid, ultra-rapid, and ionosphere) as soon as possible. We are confinced that we have now achieved this goal and that the quality of our Galileo orbit estimates is significantly better then that of our GLONASS orbit estimates and is getting close to the quality of the GPS orbit estimates. Our aim is to include the Galileo satellites in our official IGS processing during the cause of 2018.

Our BeiDou MEO results are also very good and currently at least as good as the GLONASS results. However, due to the limited number of BeiDou MEO satellites and the changes that are happening to both the MEO and IGSO satellites we do not feel confident enough to include them in our routine IGS products. These BeiDou changes are, however, very much welcomed as they do improve things significantly with BeiDou also adopting the yaw-attitude steering which is common for GNSS satellites and removing, or at least significantly reducing, the elevation dependent pseudo-range biases.

5.2 Multi-GNSS Products

At the end of 2017 ESOC has started to routinely publish its experimental multi-GNSS products on a best effort basis using the normal IGS products and naming convention. We have selected *esm* as three character indicator for our ESA/ESOC Multi-GNSS solutions. The products we provide are:

- The main directory contains our analysis center questionaire (esm_YYYYMMDD.acn)
- Daily SP3 orbits with 5 min sampling to enable proper interpolation of the eccentric satellites (Galileo and QZSS), normal IGS 15 min sampled SP3 files are *not* sufficient for interpolation of the eccentric orbits
- Daily ERP file in normal IGS format
- Daily Clock-RINEX files with 30 second sampling of the clocks
- Daily bias files with the estimated intersystem biases, relative to the GPS system
- Daily summary file

The ESA/ESOC multi-GNSS products (esm) are publicly availabe from our web-site under:
http://navigation-office.esa.int/products/gnss-products/

5.3 Sub-daily ERP

After the Unified Analysis Workshop in 2014, which took place immediately after the IGS workshop we agreed with John Gipson to retest his sub-daily ERP model. We had tested his model back in 2011 and noticed a clear reduction of the 14 day periods in the orbit overlaps. The solutions in 2011 were mainly test runs to validate our IGS reprocessing set-up and as consequently we did not spend enough time on realising the importance of this results obtain. But at the UAW in 2014 John Gipson presented the latest version of his sub-daily ERP model with as conclusion that *this is what you get from VLBI.* This model is what VLBI will give you, it may be wrong but adding additional data will not changes things! This remotivated us to look at the model but due to many several distractions we ended up testing this only in 2017 after switching to the ITRF2014. The results we got in 2017 confirmed what we found in 2011 in that the 14 day periods as observed in the orbit overlaps for GPS are greatly reduced, if not even eliminated. The difference in our solutions this time was that we also included GLONASS and Galileo. This was done to rules out any GPS specific effects. And as expected a similar reduction of the 14 day period was observed for both the GLONASS and Galileo orbits. These results were presented at the IGS workshop in Paris in 2017 Springer (2017) and in more detail at the Unified Analysis Workshop in Paris directly following the IGS workshop Otten (2017).

After the IGS and UAW workshops we performed a full IGS reprocessing using all IGS data from 1995 to 2017 day 100. Main aim from this analysis was to investigate if the station coordinates do also show a reduction of the power at the 14 day intervals. In a collaboration between ESOC and IGN, Paul Rebischung analysed our SINEX time series. His analysis confirmed the reduction of the power in the ERP estimates at the 14 day periods. Unfortunately the analysis only showed a minor reduction of the power at the 14 day periods for the station coordinates. There was a clear overall, i.e. over the full wavelengt spectrum, power reduction in the East component but it is not 100

6 Summary

The European Space Operations Centre (ESOC) of the European Space Agency (ESA) Analysis Center has continued to produce *best in class* products for the IGS. All products are generated using the Navigation Package for Earth Orbiting Satellites (NAPEOS) software. NAPEOS is a state of the art software that is highly accurate, very efficient, robust and reliable. It enables ESA/ESOC to deliver the high quality products as required for the IGS but also for the other space geodetic techniques DORIS and SLR. This is important because besides being an IGS Analysis Centre, ESA/ESOC is also an Analysis Centre of the IDS and the ILRS.

In the coming year our main focus will be on improving the orbit modelling for the different GNSS constellations. We need to improve our (a priori) box-wing models for the GPS IIF, QZSS and BeiDou satellites and handle the new GLONASS-K and BeiDou 3rd genaration satellites.

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GFZ Analysis Center Technical Report 2017

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1 Summary

During 2017, the standard IGS product generation was continued with minor changes in the processing software EPOS-8. The GNSS observation modeling still conforms to the GFZ repro-2 (2nd IGS Reprocessing campaign) settings for the IGS Final product generation. The multi-GNSS processing was continued routinely during 2017 including GPS, GLONASS, BeiDou, Galileo, and QZSS with only few exceptions from a regular submission.

2 Products

The list of products provided to the IGS by GFZ is summarized in Table 1.

3 Operational Data Processing and Latest Changes

Our EPOS-8 processing software is following the IERS Conventions 2010 (Petit and Luzum 2010). For the IGS Final, Rapid and Ultra-rapid chains approximately 200, 130, and 95 sites are used, respectively. Recent changes in the processing strategy are listed in Table 2. Only minor changes have been applied for the observation modeling in order to keep the consistency with respect to the repro-2 processing strategy. The most important change was the switch from IGb08 to IGS14 including the application of post-seismic deformations (Altamimi et al. 2016).

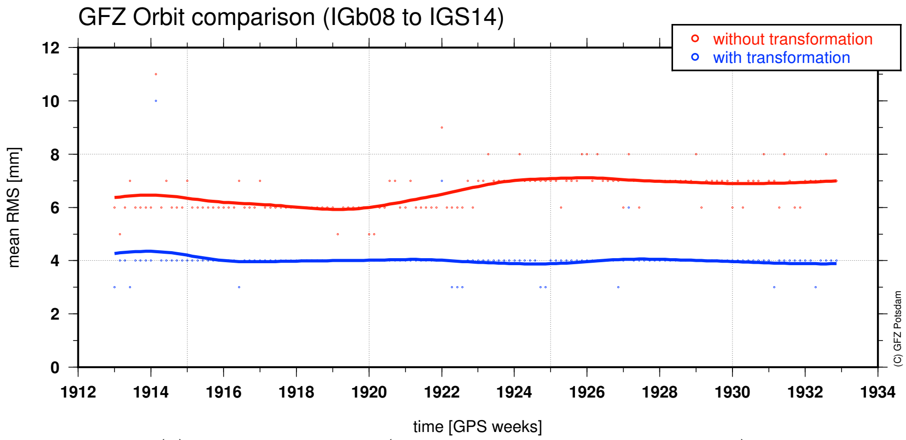
Table 1: List of products provided by GFZ AC to IGS and MGEX

IGS Final	(GLONASS since week 1579)
`gfzWWWWD.sp3`	Daily orbits for GPS/GLONASS satellites
`gfzWWWWD.sp3`	Daily orbits for GPS/GLONASS satellites
`gfzWWWWD.clk`	5-min clocks for stations and 30-sec clocks for GPS/GLONASS satellites
`gfzWWWWD.snx`	Daily SINEX files
`gfzWWWW7.erp`	Earth rotation parameters
`gfzWWWW7.sum`	Summary file including Inter-Frequency Code Biases (IFB) for GLONASS
`gfzWWWWD.tro`	1-hour tropospheric Zenith Path Delay (ZPD) estimates
IGS Rapid	(GLONASS since week 1579)
`gfzWWWWD.sp3`	Daily orbits for GPS/GLONASS satellites
`gfzWWWWD.clk`	5-min clocks for stations and GPS/GLONASS satellites
`gfzWWWWD.erp`	Daily Earth rotation parameters
IGS Ultra-Rapid	(every 3 hours; provided to IGS every 6 hours; GLONASS since week 1603)
`gfuWWWWD_HH.sp3`	Adjusted and predicted orbits for GPS/GLONASS satellites
`gfzWWWWD_HH.erp`	Earth rotation parameters
MGEX Rapid	
`gbmWWWWD.sp3`	Daily satellite orbits for GPS/GLONASS/Galileo/BeiDou/QZSS
`gbmWWWWD.clk`	30 sec (since GPS-week 1843) receiver and satellite clocks
`gbmWWWWD.erp`	Daily Earth rotation parameters
MGEX Ultra-Rapid	(since week 1869)
`gbuWWWWD_HH.sp3`	Adjusted and predicted orbits for GPS/GLONASS/Galileo/BeiDou/QZSS
`gbuWWWWD_HH.erp`	Earth rotation parameters

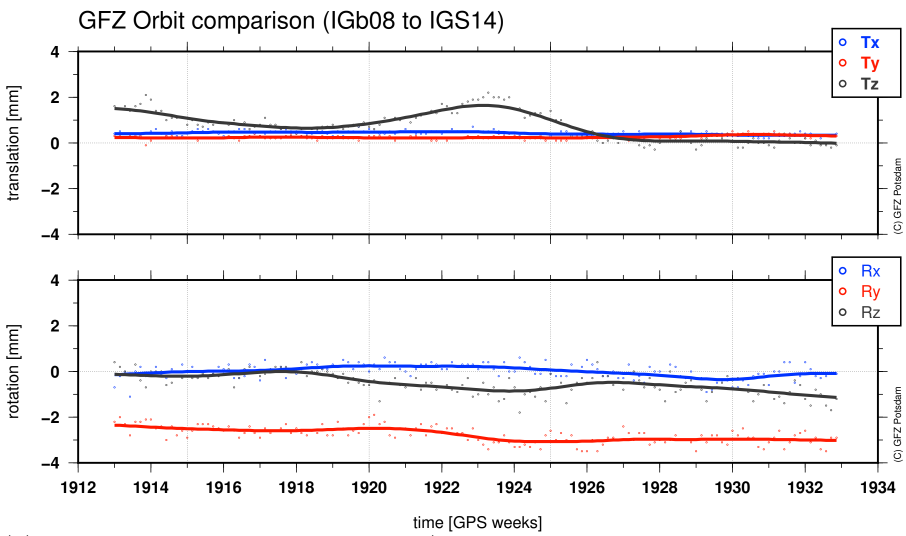
Table 2: Recent processing changes

Date	**IGS**	**IGR/IGU**	Change
2017-01-29	w1930	w1934.0	Switch to IGS14 and igs14.atx

Between GPS week 1924 (November 20th, 2016) and 1933 (January 28, 2017) GFZ operated an additional processing chain, without product submission, to assess the impact IGS14 has on derived products especially on the orbits. Figure 1(a) shows the orbit comparison between the orbits computed in the operational mode (IGb08) and in the experimental chain (IGS14) as mean RMS of position differences. This comparison was done without (*blue*) and with (*red*) estimating Helmert transformation parameters. Mean RMS values of the differences were found to be around 4 mm and around 6 mm, respectively. Figure 1(b) presents the estimated transformation parameters, which are rather stable over time. Small variations are visible in the z-translation between week 1922 and 1924,



(a) Orbit differences (mean 3D RMS over all satellites)



(b) Helmert transformation parameters (rotations are converted to distances at Earth surface)

Figure 1: Orbit comparison between GFZ orbits based on IGb08 and on IGS14

whereas, an offset of 2 mm is present in the rotation around the y-axis.

4 Multi-GNSS data processing

The IGR-like and the ultra-rapid like style multi-GNSS processing was continued in 2017 (Deng et al. 2016). The GFZ multi-GNSS solution covers 5 different systems, namely GPS, GLONASS, Galileo, BeiDou and QZSS. Figure 2 shows the total num-

Table 3: Used observation types and number of satellites (averaged) in the multi-GNSS data processing (gbm)

Satellite System	# Satellites	Observation Types
GPS	31	L1/L2
GLONASS	22	L1/L2
Galileo	17	E1/E5a
BeiDou	14	B1/B2
QZSS	1	L1/L2

ber of satellites per GNSS included in the gbm MGEX solution in 2017. The number of processed multi-GNSS stations in gbm and gbu is about 150 and 100, respectively. Currently the consumed data processing time is about 4 and 1 hour for the gbm and gbu analysis, respectively. Table 3 shows the corresponding observation type selection made for the individual GNSS. The ultra-rapid like products are identified with the gbu acronym (cf. Table 1). Both product types, gbm and gbu, are available at ftp://ftp.gfz-potsdam.de/GNSS/products/mgnss/.

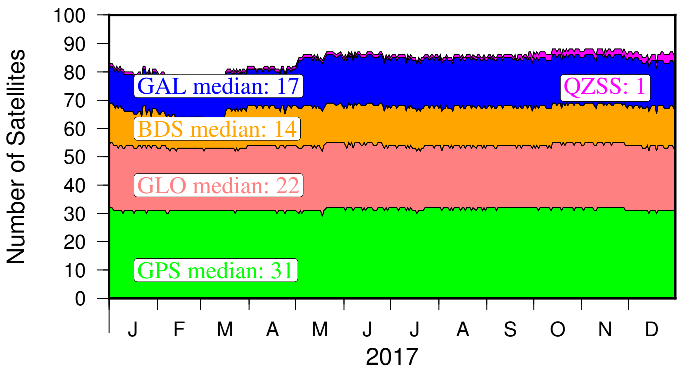


Figure 2: Total number of satellite per GNSS included in the daily multi-GNSS data processing (gbm)

5 Operational GFZ Stations

The GFZ operated global GNSS station network comprises currently 23 GNSS stations participating in the IGS tracking network. Figure 3 shows the globally distribution of these stations. Within 2017, the station Urumqi (URUM, People's Rupublic of China) was upgrade by changing the receiver to a JAVAD TRE_3 and the antenna to a JAVRINGANT_G5T NONE. The station is now capable to track GPS, GLONASS, Galileo and BeiDou. A firmware upgrade allowing QZSS tracking is under way. For 2018

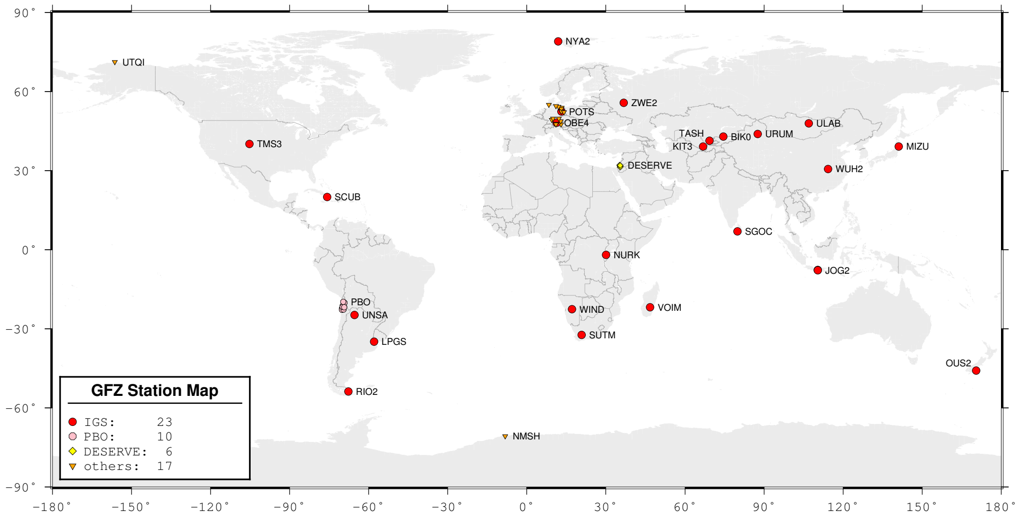


Figure 3: GNSS stations operated by GFZ

we plan similar upgrades for additional six stations. Larger data gaps occured for WIND (Windhoek, Namibia) and WUH2 (Wuhan, People's Rupublic of China) due to local internet connection problems and for NURK (Kigali, Rwanda) and ZWE2 (Zwenigorod, Russia) due to hardware problems. In the framework of the GCOS Reference Upper-Air Network project we installed a GNSS station (UTQI) at the GRUAN site in Barrow, Alaska. The station is equipped with a JAVAD TR_G3TH receiver and a JAV_GRANT-G3T NONE antenna. UTQI is capable to track GPS, GLONASS, and Galileo. After monitoring the coordinate stability within a year's period we intend to propose UTQI as IGS tracking network during summer 2018.

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CNES-CLS Technical Report 2017

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1 Introduction

In 2017, the CNES-CLS Analysis Center continued its contribution through the weekly delivery of combined final GPS-GLONASS-Galileo products using the GINS software package. The formal "GRG" GPS-GLONASS products can be downloaded from the "products/wwww" directory of any IGS archiving center while experimental "GRM" GPS-GLONASS-Galileo products are accessible from the "products/mgex/wwww" directory. The relative data weighting between the different constellations during the processing is summarized in table 1.

Table 1: Data weighting in the combined solution (in meters).

Constellation	Phase	Range
GPS	0.0035	0.35
GLONASS	0.035	2
Galileo	0.035	1

In agreement with the ACC, the switch to the ITRF2014 frame occurred week 1934 (29/01/2017). Additional changes and investigations during 2017 are detailed in the following sections. More information can also be found at: https://igsac-cnes.cls.fr/

2 Developments in Galileo data processing

We include in the processing any GPS, GLONASS or Galileo satellite as soon as its range and phase observations are available. The number of available Galileo satellites included in the "GRM" products has significantly increased in 2017 as shown in figure 1.

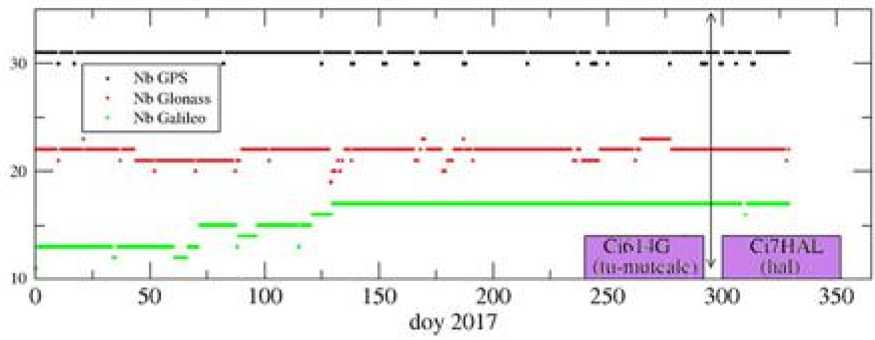

Figure 1: Number of GPS, GLONASS and Galileo satellites included in the GRM products.

With 17 tri-frequency satellites available the orbit and clock determination process becomes good enough to attempt undifferentiated Galileo phase measurements ambiguity fixing. A prerequisite is however a "reasonable" (daily) stability of the satellite "hardwar" biases. After investigation, we have observed that these biases are even more stable than for the GPS constellation and that all IGS GNSS receiver agree at the level of 0.08 cycles when observing these biases (Figure 2, Katsigianni et al. (2017)).

The preliminary results of the second step consisting in estimating the receiver bias and fixing the ambiguities are still under validation but are very encouraging. In this context, the recent delivery of the Galileo metadata by ESA was of high importance. Box&wing data, antenna thrusts and attitude laws of IOV and FOC satellites have been implemented and tested in an experimental version of the GINS software. As an example, figure 3

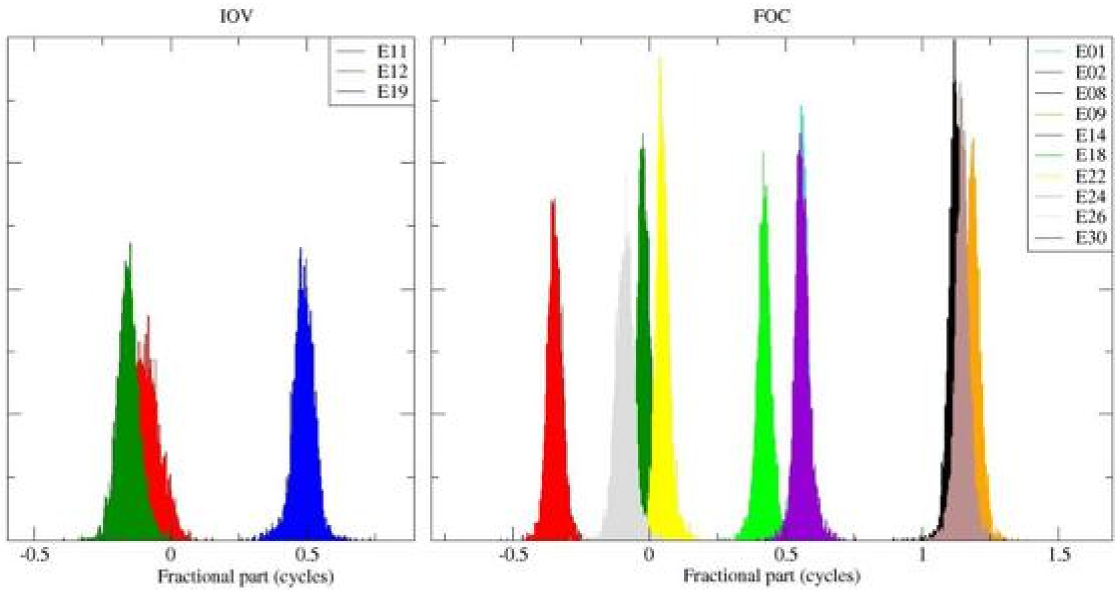

Figure 2: Galileo Wide-Lane Satellite Biases observed from the MGEX network observations.

illustrates the impact of using an improved attitude model by comparing the (de-trended) clock solution of PRN E02 satellite.

3 GNSS satellite attitude quaternions exchange

As discussed within the IGS Multi-GNSS WG, the knowledge of the satellite attitude used during the orbit/clock computation process is needed to fully exploit the precision of these products (e.g. for a PPP processing). In cooperation with Simon Banville from NRCAN we posted a format proposal for the exchange of GNSS satellite attitude information (Loyer et al. 2017): `ftp://ftpsedr.cls.fr/pub/igsac/obx/proposal_orbex_june2017.pdf` A one-day 30s sampling example (corresponding to a GRM solution), is also provided: `ftp://ftpsedr.cls.fr/pub/igsac/obx/grm19504.obx.Z` Hopefully this will contribute to a future adoption of an exchange format and will encourage ACs to provide this information.

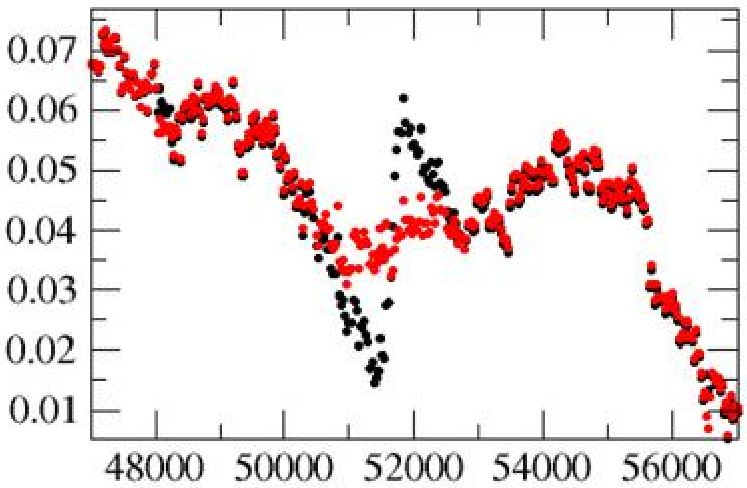

Figure 3: De-trended clock solution of E02 Galileo satellite using a yaw-steering attitude law (black) and the model provided by ESA (red) during an Earth shadow crossing (Beta=1.7○). The red curve is certainly closer to the real behavior of the atomic clock than the black one.

4 GRG tropospheric products

We have implemented the capability to produce SINEX tropospheric solutions. A comparison of our internal solution of zenithal corrections with the IGS COD and JPL solutions in presented in figure 4.

This new GRG product can be delivered routinely and will be proposed to the IGS.

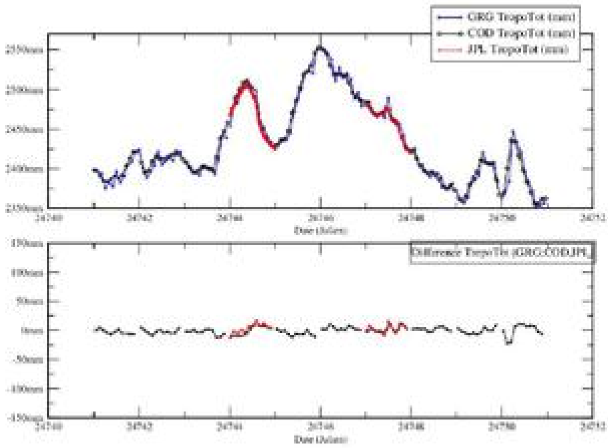

Figure 4: Total zenithal tropospheric bias for station TLSE (Toulouse, France) from COD, JPL and GRG ACs (top figure). The differences between GRG solution and the two others are represented in the bottom plot.

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JPL IGS Analysis Center Technical Report 2017

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1 Introduction

In 2017, the Jet Propulsion Laboratory (JPL) continued to serve as an Analysis Center (AC) for the International GNSS Service (IGS). We contributed operational orbit and clock solutions for the GPS satellites; position, clock and troposphere solutions for the ground stations used to determine the satellite orbit and clock states; and estimates of Earth rotation parameters (length-of-day, polar motion, and polar motion rates). This report summarizes the activities at the JPL IGS AC in 2017.

Table 1 summarizes our contributions to the IGS Rapid and Final products. All of our contributions are based upon daily solutions centered at noon and spanning 30-hours. Each

Table 1: JPL AC Contributions to IGS Rapid and Final Products.

Product	Description	Rapid/Final
jplWWWWd.sp3	GPS orbits and clocks	Rapid & Final
jplWWWWd.clk	GPS and station clocks	Rapid & Final
jplWWWWd.tro	Tropospheric estimates	Rapid & Final
jplWWWWd.erp	Earth rotation parameters	Rapid(d=0-6), Final(d=7)
jplWWWWd.yaw	GPS yaw rate estimates	Rapid & Final
jplWWWWd.snx	Daily SINEX file	Final
jplWWWW7.sum	Weekly solution summary	Final

of our daily solutions is determined independently from neighboring solutions, namely without applying any constraints between solutions. High-rate (30-second) Final GPS clock products are available from 2001 onwards.

The JPL IGS AC also generates Ultra-Rapid orbit and clock products for the GPS constellation. These products are generated with a latency of less than 2.5 hours and are updated hourly (Weiss et al. 2010). Although not submitted to the IGS, our Ultra-Rapid products are available in native GIPSY and GipsyX formats at:

- ftp://sideshow.jpl.nasa.gov/pub/JPL_GPS_Products/Ultra
- ftp://sideshow.jpl.nasa.gov/pub/JPL_GNSS_Products/Ultra

2 Processing Software and Standards

On 29 Jan 2017 (start of GPS week 1934) we switched from using GIPSY (version 6.4) to the GipsyX to create all our orbit and clock products. At the switch we also started to produce rapid products in IGS14 while continuing to produce final products in IGb08.

In our operations, we have adopted the data processing approach used for our repro2 reprocessing which had the following improvements from our previous data processing strategy:

1. Application of second order ionospheric corrections (Garcia-Fernandez et al. 2013).
2. Revised empirical solar radiation pressure model named GSPM13 (Sibois et al. 2014).
3. Antenna thrust models per IGS recommendations.
4. Modern ocean tide loading, using GOT4.8 (Ray 2013) (appendix) instead of FES2004 (Lyard et al. 2006).
5. GPT2 troposphere models and mapping functions (Lagler et al. 2013).
6. Elevation-dependent data weighting.

A complete description of our current operational processing approach, also used for repro2, can be found at:

ftp://sideshow.jpl.nasa.gov/pub/JPL_GPS_Products/readme.txt

We continue to use empirical GPS solar radiation pressure models developed at JPL instead of the DYB-based strategies that are commonly used by other IGS analysis centers. This choice is based upon an extensive evaluation of various internal and external metrics after testing both approaches with the GIPSY/OASIS software (Sibthorpe et al. 2011).

3 GipsyX Overview

For several years we have been developing a replacement to GIPSY called GipsyX which has the following features:

1. GipsyX is the C++/Python3 replacement for both GIPSY and Real-Time GIPSY (RTG).
2. Driven by need to support both post-processing and real-time processing of multiple GNSS constellations.
3. Can already process data from GPS, GLONASS, Beidou, and Galileo.
4. Supports DORIS and SLR data processing.
5. Multi-processor and multi-threaded capability.
6. Single executable replaces multiple GIPSY executables: model/oi, filter. smoother, ambiguity resolution.
7. Versatile PPP tool (gd2e) to replace GIPSY's gd2p.
8. Similar but not identical file formats to current GIPSY.
9. Runs under Linux and Mac OS.
10. First GipsyX beta-version released to the GIPSY user community in December 2016
11. Available under similar license to GIPSY license (see `https://gipsy-oasis.jpl.nasa.gov/index.php?page=software` for more details)

In parallel with the GipsyX development we have also developed new Python3 operational software that uses GipsyX to generate the rapid and final products that we deliver to the IGS as well as generating our ultra-rapid products that are available on our ftp site.

4 Recent Activities

Recent activities are well summarized by presentations at the 2017 IGS workshop in Paris and 2017 Fall AGU meeting in New Orleans. These include:

- Results from the JPL IGS Analysis Center IGS14 Reprocessing Campaign (Ries et al. 2017)
- Impact of modern Earth orientation models on GPS precise orbit determination (Sibois and Desai 2017a)
- Improved Modeling of GPS Block IIF Satellites for the GSPM13 Solar Radiation Pressure Model (Sakumura et al. 2017)

- Ensuring a smooth operational transition from GIPSY-OASIS to GipsyX: product verification and validation overview (Sibois et al. 2017b)
- Status and Future Plans at the JPL IGS Analysis center (Murphy et al. 2017)

5 Future Work

We intend to release the GPS orbit and clocks in IGS14 from our reprocessing campaign from 2002 onwards in April 2018. Simultaneously with this we will also start to create and deliver final orbit and clock products in IGS14. Our longer term goal is to generate other GNSS constellation orbit and clock products using this new software as well as adding the capability to process other non-GNSS geodetic data.

6 Acknowledgments

The work described in this report was performed at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

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Sakumura C., A. Sibois, A. Sibthorpe, and D. Murphy Improved Modeling of GPS Block IIF Satellites for the GSPM13 Solar Radiation Pressure Model IGS Workshop, Paris, July 3-7., 2017

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Sibois, A., and S. Desai, Impact of modern Earth orientation models on GPS precise orbit determination, IGS Workshop, Paris, July 3-7., 2017a

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MIT Analysis Center Technical Report 2017

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1 Introduction

In this report, we discuss results generated by the MIT analysis center (AC) both for submissions of weekly final IGS solutions and our weekly combination of SINEX files from MIT and the other eight IGS analysis centers that submit final SINEX files. We present here analysis of the networks we process, comparison between our position estimates and those from other IGS analysis centers and the impact of the IGb08 to IGS14 transition. We also address in section 4, the inconsistency between the data files containing the spherical harmonic coefficients and the formulation for the FES2004 ocean model as given in the IERS2010 conventions.

2 Overview of MIT processing

The MIT analysis for IGS final orbits, clocks and terrestrial reference frame uses the GAMIT/GLOBK software versions 10.61 and 5.29 (Herring et al. 2015). The GAMIT software uses a double-difference estimator. In order to efficiently process a large global network sub-networks are used. Each day, 350 stations are included in the combined network which is composed of seven individual networks each with 50 stations and pairs of stations that couple each sub-network to every other sub-network. These networks are generated independently each day and depend of the data that is available in the IGS and other data archives. We search CDDIS, UNAVCO, SOPAC, Geosciences Australia and BKG for RINEX data. Each network is seeded with four distant sites (not all sites need to be available) and the seven networks are sequentially filled, first from a list of 378 IGS sites and then from other sites around the world that will fill in regions not covered by the IGS sites. Starting on September 23, 2017 we excluded GMSD since it stopped providing L2 data. Sites are added one-at-time to each network rather than making one

Table 1: MIT products submitted for weekly finals analysis.

File	Description
mitWWWW7.sum.Z	Summary file. WWWW is GPS week number.
mitWWWW7.erp.Z	Earth rotation parameters for 9-days, IGS format
mitWWWWn.sp3.Z	Daily GPS satellite orbits (n=0-6)
mitWWWWn.clk.Z	Daily GPS satellite clocks (n=0-6)
mitWWWW.snx.Z	Daily GPS coordinate and EOP SINEX file.

Table 2: MIT products submitted for daily combinations of IGS final AC SINEX files.

File	Description
migWWWWn.snx	Combined sinex file from all available analysis centers (n=0-6, WWWW GPS week number)
migWWWWn.sum	Name of this summary file (n=0-6)
migWWWWn.res	File of the individual AC position estimates residuals to the combined solution for the week. (n=0-6)

complete network before moving the next. The sequential approach makes each network as globally distributed as possible. Pairs of overlap stations are selected from the stations in each network to join the networks together. No station is used more than twice in this approach. The network solutions and parameterized orbit models are combined with the GLOBK software. The GAMIT solutions estimate parameters for the full Bernese Empirical Code Orbit model (ECOM) (Beutler et al. 1994): 6 initial conditions, 3 constant radiation parameters and 3 pairs of once-per-revolution (OPR) radiation parameters. In the GLOBK combination stage, we often force the OPR terms for all but the B-axis to zero. Our treatment of the OPR terms remained un-changed from last year. The GAMIT clock solutions, which have not been used in the IGS clock estimates since mid-2015, are based on un-differenced data analysis using the MIT orbit, station positions, and Earth orientation parameter estimates. The clock estimates are generated in a post-processing step using the GAMIT phase cleaning program. This procedure also remains unchanged. At the start of GPS week 1934 (2017/01/29) we switched the ANTEX file, the reference frame apriori coordinate file and list of the reference frame stations to the IGS14 values. With these changes the number of reference frame sites dropped from ∼60 IGb08 sites each day to ∼45 IGS14 sites.

In addition to weekly final processing, we also generate combined SINEX processing from the combination of all eight IGS ACs contributing to the IGS finals. We do this in our role as an associate analysis center (AAC). The procedures here are unchanged except for the transition to In Tables 1 and 2 we list the products submitted by MIT in our AC and AAC roles.

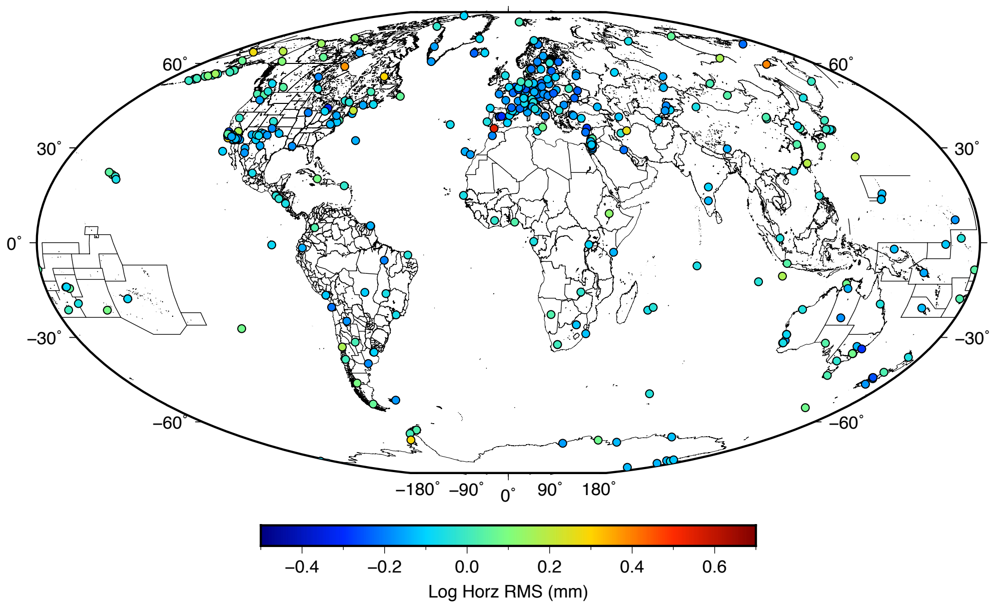

Figure 1: Log (base10) of the RMS scatter of the horizontal position estimates from the network of 433 stations processed more than 5 times by MIT in 2017. Each daily network has 350 station and the networks evolve with time depending on data availability and geometry. An additional 33 stations were used less than or equal 5 times. The cooler colors are all less than 1 mm RMS scatter while the warmer colors are greater than 1 mm scatter.

The network of stations processed by MIT in 2016 is shown in Figure 1. The figure shows the weighted root-mean-square (WRMS) scatter of the horizontal coordinates of nearly all of the stations included in the MIT finals processing. Stations that were used just a few times (15 stations in all) are not included in the plot. Only linear trends were removed from the time series. Figure 2 shows histograms of the WRMS in all three topocentric coordinates after the removal of linear trends from the time series. The median WRMS scatters of the 433 sites, measured more than five times, included in the statistics are 1.5 mm in North and East and 5.2 mm in height. No annual signals were removed. These values are very similar to last year's report.

3 Position repeatability and comparison to other ACs

We can also compare the MIT daily position estimates with those of other analysis centers based on the AAC combinations performed at MIT. The MIG combined solution is used for comparison with the official IGS combination preformed at IGN and generally matches the IGN solution at the level of 0.1-0.2 mm in north and east (NE) and 0.7-1.0 mm in height (U). The two analyses use different methods to determine AC weighting and different

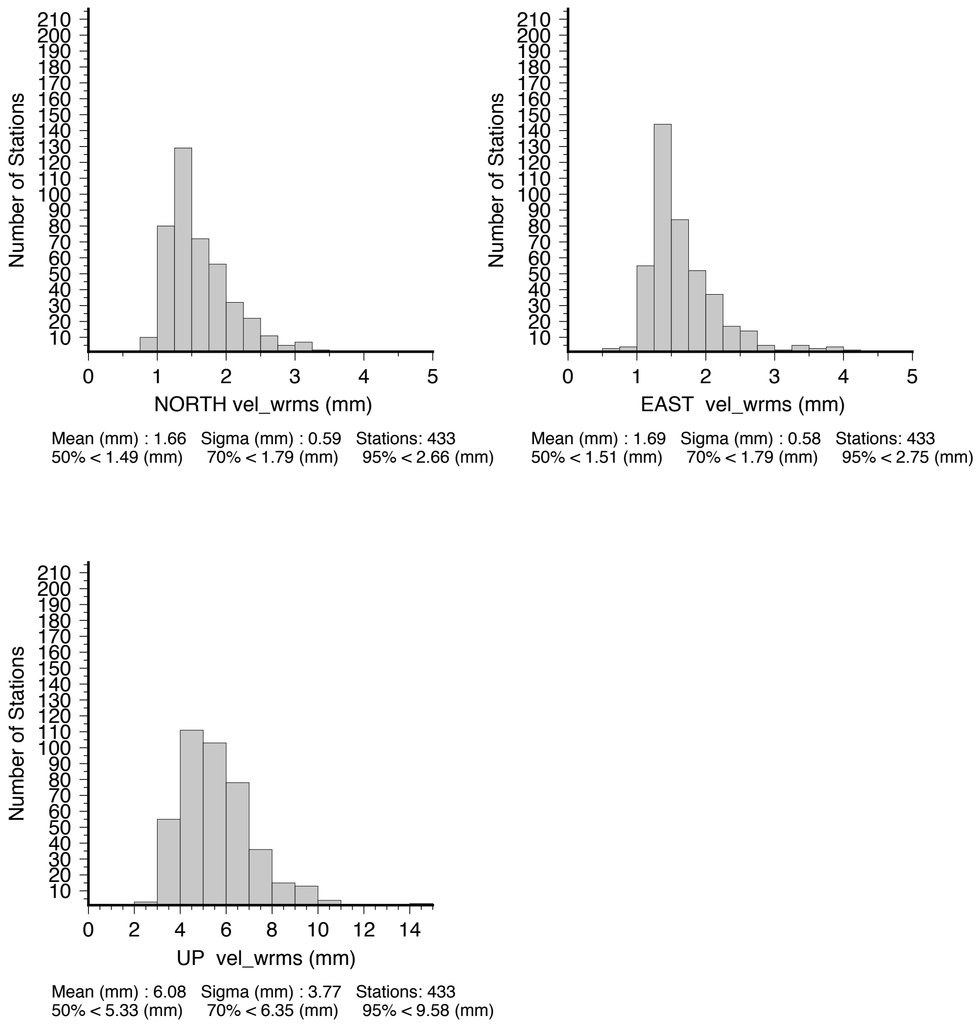

Figure 2: Histogram of the weighted root-mean-square (WRMS) scatter of daily position estimates of site used more than 5 times for 2017 after removal linear trends and elimination of gross outliers (5 times WRMS scatter). The median scatters are similar to last year with 1.5 mm horizontal and 5.3 mm vertical.

Table 3: Comparison of the fits to the IGb08/IGS14 reference frame (RF) and daily combined solutions for RF sites in the MIT and other AC daily final SINEX files. Typically, 50 sites are used in the comparison for IGS14 and 60 sites for IGb08. The switch to IGS14 took place at the start of week 1934, Jan 29, 2017.

	N (mm)	E (mm)	U (mm)	N (mm)	E (mm)	U (mm)
MIT	2.86	2.57	7.89	0.98	1.00	2.96
COF	2.91	3.08	8.07	1.17	1.25	3.51
EMR	2.68	2.43	7.60	1.11	0.98	3.30
ESA	2.83	3.03	8.21	0.93	0.96	4.05
GFZ	2.64	2.81	8.11	0.97	1.00	3.26
GRG	3.16	2.96	9.33	1.61	1.33	5.41
JPL	3.06	2.79	6.80	1.36	1.49	5.45
NGS	3.14	2.66	8.25	1.26	1.39	4.02
SIO	3.03	2.92	8.40	1.48	1.55	3.85

selection of sites. In Figure 3, we show the WRMS scatter of the daily fits to 60-70 IGb08 reference frame sites from each of the IGS ACs and the combined SINEX solution with the weights assigned to each AC consistent with the fit of the AC to combination of the other ACs. There is good consistency between the ACs. Figure 4 shows the WRMS scatter between the AC and either IGb08 (first 28 days) or IGS14 (after Jan 29). The transition to IGS14 can be clearly in the North and East components while not being so clear in the height. While the AC results look similar, there are differences in the mean of the RMS differences. An interesting feature in Figure 4, is that when comparing to IGS14, JPL which has yet to switch to IGS14 has smaller RMS differences than any of the ACs that have switched. We suspect this is due to scale rate of GPS seen in the ITRF2014 system. The IGS scale was matched to ITRF2014 in 2010 and since then has been slowly drifting away from the IGS scale. The scale drift was negligible in ITRF08/IGb08 and the agreement of JPL results suggests that since the remained in the IGb08 frame, they do not see the systematic scale difference that has developed by 2017. Table 3 gives the mean RMS differences for each AC with respect IGb08/IGS14 and respect to the combination. This table shows that on average the MIT solution provides a very good match to the combined solution with sub-millimeter horizontal WRMS and 3.3 mm WRMS in height. We also compute the chi-squared per degree of the fits and all AC's have similar chi-squared values indicating that no one center dominates the combination.

4 Clarification of IERS 2010 Standard description of the ocean tide potential model

The current ocean tide explanation and the associated file of spherical harmonics is confusing in the IERS 2010 conventions because of an error in the tabulated values of the zonal

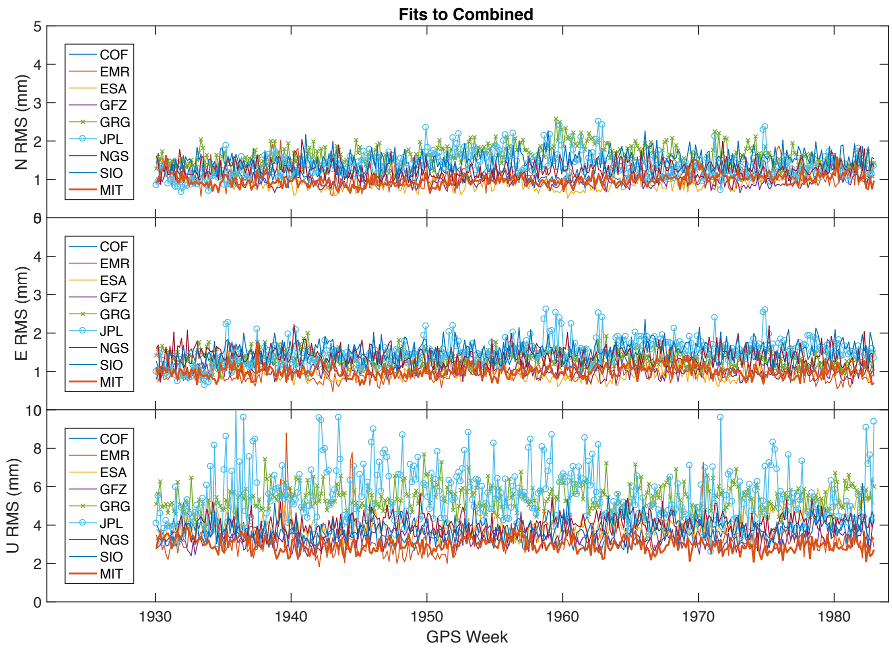

Figure 3: RMS scatters of the fits of the different IGS ACs to the MIG combined solution for 2017.

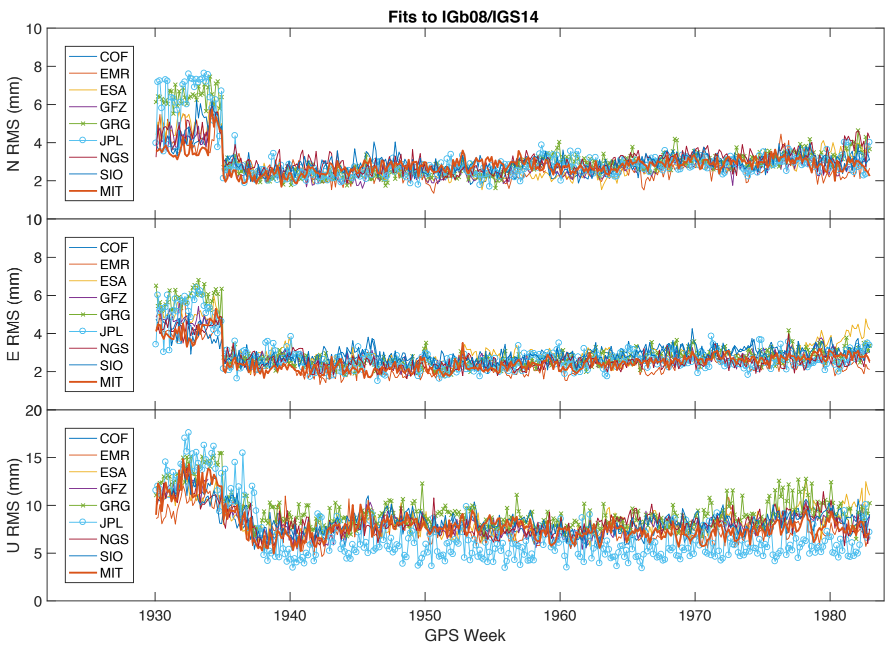

Figure 4: RMS scatters of the fits to IGb08, prior to week 1934, and IGS14 this week and after for the analyses in 2017.

Table 4: Header and example coefficients from fes20014_Cnm-Snm.dat.

```
Coefficients to compute variations in normalized Stokes coefficients (unit = 10^-12)
Ocean tide model: FES2004 normalized model (fev. 2004) up to (100,100)
(long period from FES2002 up to (50,50) + equilibrium Om1/Om2, atmospheric tide NOT included)
Doodson Darw  l   m     DelC+     DelS+       DelC-     DelS-
 55.565 Om1   2   0   6.58128  -0.00000    -0.00000  -0.00000
 55.575 Om2   2   0  -0.06330   0.00000     0.00000   0.00000
 56.554 Sa    1   0  -0.00000  -0.00000    -0.00000  -0.00000
 56.554 Sa    2   0   0.56720   0.01099    -0.00000  -0.00000
âĂę
145.555 O1    2   0   2.24382   5.10695    -0.00000  -0.00000
145.555 O1    3   0  -2.54160   2.49013    -0.00000  -0.00000

145.555 O1    2   1 -16.83767 -18.02652     9.64796   5.54088
145.555 O1    3   1  -1.71828  13.48984   -10.07295  -4.41731

145.555 O1    2   2   3.83177  10.41277     1.01777  -0.34218
145.555 O1    3   2   8.66519   7.41124    -4.59111  -2.09403
```

harmonics in the FES2004 Cnm Snm data file. The confusion arises because when the IERS formulation is applied to the tabular values for the zonal terms, S_{n0} coefficients are generated when these coefficients should not exist. The question raised by these non-zero coefficients is whether the formulation and the table are consistent with each other, or does the table contain cosine and sine terms for the C_{nm} and S_{nm} coefficients? The latter interpretation is consistent with the way the zonal terms appear in the file but inconsistent with the formulation given in Chapter 6 of the IERS conventions. Chapter is available as PDF file TechnNote36/tn36_079.pdf. We explore the correct interpretation here and conclude that the zonal coefficients in the IERS data files are incorrect.

The ocean tide formulation is given by Equation (6.15) from Chapter 6 of the IERS conventions.

$$\left[\Delta\bar{C}_{nm} - i\Delta\bar{S}_{nm}\right](T) = \sum_{f}\sum_{+}^{-}\left(C^{\pm}_{f,nm} \mp iS^{\pm}_{f,nm}\right)e^{\pm i\theta_f(t)} \qquad \text{(IERS 6.15)}$$

where f sums over frequencies in the tidal expansion and the $\pm$ terms are prograde and retrograde terms. The standards point to fes20014_Cnm-Snm.dat (the link has space between 4 and C rather than _ which is the character in the file name on the ftp site) as the source for the coefficients on the RHS of IERS 6.15. The link is `ftp://tai.bipm.org/iers/conv2010/chapter6/tidemodels/fes2004_Cnm-Snm.dat` The header of this file with example entries for the low degree O1 coefficients are given in table 4.

The columns in fes20014_Cnm-Snm.dat correspond to $DelC+ = C^+_{f,nm}$, $DelS+ = S^+_{f,nm}$, $DelC- = C^-_{f,nm}$ and $DelS- = S^-_{f,nm}$. Expanding (IERS 6.15) into the summations needed to compute $Delta\bar{C}_{nm}$ and $\Delta\bar{S}_{nm}$ yields

$$\Delta\bar{C}_{nm} = \sum_f (C^+_{fnm} + C^-_{f,nm})\cos\theta_f(t) + (S^+_{f,nm} + S^-_{f,nm})\sin\theta_f(t) \tag{1}$$

$$\Delta\bar{S}_{nm} = \sum_f (S^+_{fnm} - S^-_{f,nm})\cos\theta_f(t) - (C^+_{f,nm} + C^-_{f,nm})\sin\theta_f(t) \tag{2}$$

There is a clear problem with the FES2004 tables when equation (3) is used to compute the zonal $\Delta\bar{S}_{n0}$ terms. Based on the tabulated values in the fes20014_Cnm-Snm.dat file, and the non-zero values of $S^+_{f,n0}$ and $C^+_{f,n0}$ for the zonals, equation (2) will generate non-zero values for $\Delta\bar{S}_{n0}$ which is not expected and raises the question whether the column entries in fes20014_Cnm-Snm.dat file are prograde and retrograde terms or are they cosine and sine arguments for $\Delta\bar{C}_{nm}$ and $\Delta\bar{S}_{nm}$ directly. With the latter interpretation, the last two columns being zero for the $\Delta\bar{S}_{nm}$ terms would generate zero zonal coefficients as would be expected.

The EOT11a tidal model documentation allows this question to be resolved. The web site for EOT11a gives documentation `ftp://ftp.sirgas.org/pub/EOT11a/doc/TN_EOT11a.pdf` and a zip file that contains the files with the coefficients and Matlab code that allows the coefficients and tidal potential to be computed at any time and at any location. The files for EOT11a are given separately for tidal constituent and for cosine and sine terms. For EOT11a, the corresponding equations to Equations (1) and (2) are

$$\Delta\bar{C}_{nm} = \sum_s cnmCos\cos\theta_s(t) + cnmSin\sin\theta_s(t) \tag{3}$$

$$\Delta\bar{S}_{nm} = \sum_s snmCos\cos\theta_s(t) + snmSin\sin\theta_s(t) \tag{4}$$

and the cosine and sine terms of the ΔC_{nm} and ΔS_{nm} coefficients are given. The EOT11a documentation uses s to denote the tidal constituent. Examples for the O1-tide are given in table 5 and 6.

Comparison of the two sets of files shows that the unit in the header of fes20014_Cnm-Snm.dat is incorrect. The header says (unit = 10$\hat{-}$12) but comparison to EOT11a shows the units are 10$\hat{-}$11 i.e., the value need to be multiplied by 1.e-11 to generate the correct coefficients. Also, comparison of equations (1) and (2) with (3) and (4) show the relationship between the coefficients in the two formulations are

$$cnmCos = (C^+_{f,nm} + C^-_{f,nm}) \tag{5a}$$

$$cnmSin = (S^+_{f,nm} + S^-_{f,nm}) \tag{5b}$$

$$snmCos = (S^+_{f,nm} - S^-_{f,nm}) \tag{5c}$$

$$snmSin = -(C^+_{f,nm} - C^-_{f,nm}) \tag{5d}$$

Table 5: eot11a/eot11a.O1.cos.gfc

```
modelname              EOT11a
product_type           gravity_field
* Roman Savcenko, Wolfgang Bosch
* Converted to spherical harmonics by Torsten Mayer-Guerr, Daniel Rieser
* Full tidal potential (inlcudes loading potential)
* Doodson-Wartburg Phase correction is already applied:
*   cnm(t) = cnmCos*cos(theta(t)) + cnmSin*sin(theta(t))
*   snm(t) = snmCos*cos(theta(t)) + snmSin*sin(theta(t))
* with
*  theta is the tidal phase angle computed from the doodson fundamentals
earth_gravity_constant 3.9860044150e+14
radius                 6.3781363000e+06
max_degree             120
norm                   fully_normalized
errors                 no
key   L   M       C                   S
end_of_head ========================================
gfc     0    0  0.000000000000e+00  0.000000000000e+00
gfc     1    0  2.690498205244e-10  0.000000000000e+00
gfc     1    1 -2.709655673648e-11 -5.694583375998e-11
gfc     2    0  1.956198512129e-11  0.000000000000e+00
gfc     2    1 -7.441043181476e-11 -2.390142967514e-10
gfc     2    2  4.785684417959e-11  1.078945423845e-10
gfc     3    0 -2.615401117822e-11  0.000000000000e+00
gfc     3    1 -1.180580331892e-10  1.807202229897e-10
gfc     3    2  4.130398890282e-11  9.375442654191e-11
```

Table 6: eot11a/eot11a.O1.sin.gfc

```
modelname               EOT11a
product_type            gravity_field
âĂę Headers are same as above and have been removed
key   L   M       C                   S
end_of_head ========================================
gfc     0    0  0.000000000000e+00  0.000000000000e+00
gfc     1    0  2.629972037389e-11  0.000000000000e+00
gfc     1    1  1.136163906226e-10  7.925630339578e-11
gfc     2    0  4.943867952441e-11  0.000000000000e+00
gfc     2    1 -1.261269533105e-10  2.633540349350e-10
gfc     2    2  9.845924326557e-11 -2.451748765211e-11
gfc     3    0  2.432286207049e-11  0.000000000000e+00
gfc     3    1  8.810154956196e-11 -8.273350744888e-11
gfc     3    2  5.736193193028e-11 -1.311092110214e-10
```

We can also invert equations (5) to express the FES2004 coefficients as functions of the EOT11a values.

$$C^{+}_{f,nm} = (cnmCos - snmSin)/2 \tag{6a}$$
$$S^{+}_{f,nm} = (snmCos + cnmSin)/2 \tag{6b}$$
$$C^{-}_{f,nm} = (cnmCos + snmSin)/2 \tag{6c}$$
$$S^{-}_{f,nm} = (cnmSin - snmCos)/2 \tag{6d}$$

When we make this comparison for non-zonal terms and applying the correct scaling factor for the FES2004 values we find that the FES2004 and EOT11a coefficients match at the level expected for different durations and data used to derive the two models. This comparison is shown for the O1 tide in Tables 7. Other tides such as M2 also match for non-zonal terms.

The non-zonal coefficients match to the level of agreement expected for models that were developed from different spans of data. For the zonal terms, the formulations do not match as would be expected based on the observation that the FES formulation generated non-zero zonal S coefficients. As can been seen in Table 8, the FES coefficients generate non-zero zonal S coefficients and the EOT11a type coefficients generated from the FES prograde, retrograde values are incorrect. The error in the FES2004 zonal coefficients lies in the zero coefficients for the retrograde terms. Given equation (2) above, we should not expect the retrograde terms to be zero for zonal coefficients. In order, to correctly the generate zonal terms, the FES2004 prograde terms for the zonal terms need to be halved and the retrograde terms need to be made equal to the prograde terms. This correction has

Table 7: Comparison of O1 low degree and order terms from EOT11a and FES2004. Here the lines starting EOT EOT are the coefficients from the EOT11a model; FES EOT lines are calculations of the EOT coefficients from the FES values using equations 5; EOT FES lines are the EOT11a values in the FES form computed from equations 6; and FES FES are the FES coefficients given in the FES2004_Cnm-Snm.dat file with the 1.e-11 multiplier. All values here should be multiplied by 1.e+11.

```
Degree and Order 2 1 Tide O1
EOT EOT C/Snm    -7.44104   -23.90143   -12.61270    26.33540
FES EOT C/Snm    -7.18971   -23.56740   -12.48564    26.48563
EOT FES CS+-    -16.88822   -18.25706     9.44718     5.64437
FES FES CS+-    -16.83767   -18.02652     9.64796     5.54088

Degree and Order 2 2 Tide O1
EOT EOT C/Snm     4.78568    10.78945     9.84592    -2.45175
FES EOT C/Snm     4.84954    10.75495    10.07059    -2.81400
EOT FES CS+-      3.61872    10.31769     1.16697    -0.47176
FES FES CS+-      3.83177    10.41277     1.01777    -0.34218

Degree and Order 3 2 Tide O1
EOT EOT C/Snm     4.13040     9.37544     5.73619   -13.11092
FES EOT C/Snm     4.07408     9.50527     5.31721   -13.25630
EOT FES CS+-      8.62066     7.55582    -4.49026    -1.81962
FES FES CS+-      8.66519     7.41124    -4.59111    -2.09403

Degree and Order 3 3 Tide O1
EOT EOT C/Snm    -2.25678    -5.76605   -18.79796    20.78643
FES EOT C/Snm    -2.06217    -5.93270   -18.60522    21.10409
EOT FES CS+-    -11.52160   -12.28200     9.26483    -6.51595
FES FES CS+-    -11.58313   -12.26896     9.52096    -6.33626
```

Table 8: Same as Table 3 but computed for the O1 zonal coefficients.

```
Degree and Order 2 0 Tide O1
EOT EOT C/Snm     1.95620    0.00000    4.94387    0.00000
FES EOT C/Snm     2.24382    5.10695    5.10695   -2.24382
EOT FES CS+-      0.97810    2.47193    0.97810    2.47193
FES FES CS+-      2.24382    5.10695   -0.00000   -0.00000

Degree and Order 3 0 Tide O1
EOT EOT C/Snm    -2.61540    0.00000    2.43229    0.00000
FES EOT C/Snm    -2.54160    2.49013    2.49013    2.54160
EOT FES CS+-     -1.30770    1.21614   -1.30770    1.21614
FES FES CS+-     -2.54160    2.49013   -0.00000   -0.00000
```

Table 9: FES2004 zonal coefficients fixed: Prograde term divided by two and the retrograde terms set equal to the prograde terms.

```
Degree and Order 2 0 Tide O1
EOT EOT C/Snm     1.95620    0.00000    4.94387    0.00000
FES EOT C/Snm     2.24382    0.00000    5.10695   -0.00000
EOT FES CS+-      0.97810    2.47193    0.97810    2.47193
FES FES CS+-      1.12191    2.55348    1.12191    2.55348
Degree and Order 3 0 Tide O1
EOT EOT C/Snm    -2.61540    0.00000    2.43229    0.00000
FES EOT C/Snm    -2.54160    0.00000    2.49013   -0.00000
EOT FES CS+-     -1.30770    1.21614   -1.30770    1.21614
FES FES CS+-     -1.27080    1.24507   -1.27080    1.24507
```

been made in Table 9 and we see now the FES2005 matches EOT11a with the expected differences.

The zonal coefficients in the FES2004_Cnm-Snm.dat are inconsistent with the formulation given in equation 6.15 of the IERS standards. Although not shown here, equation 6.21 and the ftp://tai.bipm.org/iers/conv2010/chapter6/tidemodels/fes2004.dat file have the same inconsistency. In a prograde/retrograde formulation, the retrograde terms cannot be zero for zonal terms as they are in the two files above. For the zonal terms, the prograde and retrograde $C^{\pm}$ need to be equal and half the values given the current files. Similarly, the $S^{\pm}$ terms must be equal and half the value given in the data files. The C_{n0} coefficients are the sum of the prograde and retrograde terms and the Sn0 coefficients are the difference. Therefore, when the coefficients are equal, the difference is zero for the S_{n0} coefficients as would be expected.

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NGS Analysis Center Technical Report 2017

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1 Introduction

In 2017, NGS continued to serve as an IGS analysis center and a regional data center. This report summarizes the routine analysis and data center activities conducted at the National Geodetic Survey (NGS), and all significant changes that occurred during the year 2017.

2 Core Analysis Center Products

There were no changes in the NGS analysis center products (see Table 1) for 2017. Please refer to the Analysis Coordinator website (http://acc.igs.org) for combination statistics of the NGS analysis center products.

3 Analysis Center Processing Software and Strategies

For details about the models and strategies used, please refer to the NOAA/NGS Analysis Strategy Summary (ftp://igs.org/pub/center/analysis/noaa.acn).

Changes in the models and strategies to the processing software include:

- Week 1933 (2017-01-22)
  The reference frame for all the products has been switched from IGb08 to IGS14.

Table 1: NGS Analysis Center Products

Product	Description
Final (weekly)	
`ngswwwwd.sp3`	GPS only
`ngswwwwd.snx`	PAGES software suite (5.97 - 5.101)
`ngswwww7.erp`	Orbits, ERP and SINEX
Rapid (daily)	
`ngrwwwwd.sp3`	GPS only
`ngrwwwwd.erp`	PAGES software suite (5.97 - 5.101)
	Orbits, ERP and SINEX
	Daily submission for IGR combination
Ultra-Rapid (hourly)	
`nguwwwwd.sp3`	GPS only
`nguwwwwd.erp`	PAGES software suite (5.97 - 5.101)
	Orbits and ERP
	4 times a day submission for IGU combination

- Week 1971 (2017-10-15)
  Software for final orbit product generation has been migrated from Solaris OS to Linux. Effect upon products should be negligible.
- Week 1973 (2017-10-29)
  Software for rapid orbit product generation has been migrated from Solaris OS to Linux. Effect on products should be negligible.

4 Regional Data Center Core Products

During 2017, NGS contributed data from the sites listed in Table 2 to the IGS Network.

As a Regional Data Center, NGS also facilitated data flow for the sites given in Table 3 .

Please refer to the IGS Network website (`http://igs.org/network`) for site logs, photos, and data statistics for the sites serviced by the NGS regional data center.

Table 2: Site contributed by the NGS to the IGS network during 2017.

Site	Location	Lat.	Long.	Receiver Type	System
ASPA	Pago Pago, American Samoa	-14.33	-170.72	TRIMBLE NETR5	GPS+GLO
BARH	Bar Harbor, ME, USA	44.39	-68.22	LEICA GRX1200GGPRO	GPS+GLO
BRFT	Eusebio, Brazil	-3.88	-38.43	LEICA GRX1200PRO	GPS
BRMU	Bermuda, UK	32.37	-64.70	LEICA GRX1200GGPRO	GPS+GLO
CNMR	Saipan, CNMI, USA	15.23	145.74	TRIMBLE NETR5	GPS+GLO
GUUG	Mangilao, Guam, USA	13.43	144.80	TRIMBLE NETR5	GPS+GLO
HNPT	Cambridge, MD, USA	38.59	-76.13	LEICA GRX1200GGPRO	GPS+GLO
USNO	Washington, DC, USA	38.92	-77.07	ASHTECH Z-XII3T	GPS
WES2	Westford, MA, USA	42.61	-71.49	LEICA GR50	GPS+GLO +GAL

Table 3: Sites where NGS is facilitating data flow as a Regional Data Center.

Site	Location	Lat.	Long.	Receiver Type	System
BJCO	Cotonou, Benin	6.38	2.45	TRIMBLE NETR5	GPS+GLO
GUAT	Guatemala City, Guatemala	14.59	-90.52	LEICA GRX1200GGPRO	GPS+GLO
ISBA	Baghdad, Iraq	33.34	44.44	TRIMBLE NETR5	GPS+GLO
MANA	Managua, Nicaragua	12.15	-86.25	TRIMBLE NETR9	GPS
WUHN	Wuhan, China	30.53	114.36	TRIMBLE NETR9	GPS+GLO

5 Acknowledgments

The analysis and data center teams wish to express our gratitude to NGS management: Director Juliana Blackwell, Deputy Director Brad Kearse, Division Chief Steve Hilla, Division Chief Srinivas Reddy and Division Chief Dr. Dan Roman, for their support of this work as fundamental activities of NGS. For information about how these activities fit into NGS plans, see the National Geodetic Survey Ten-Year Strategic Plan 2013-2023 (http://geodesy.noaa.gov/web/news/Ten_Year_Plan_2013-2023.pdf).

USNO Analysis Center Technical Report 2017

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1 Introduction

The United States Naval Observatory (USNO), located in Washington, DC, USA has served as an IGS Analysis Center (AC) since 1997, contributing to the IGS Rapid and Ultra-rapid Combinations since 1997 and 2000, respectively. USNO contributes a full suite of rapid products (orbit and clock estimates for the GPS satellites, earth rotation parameters (ERPs), and receiver clock estimates) once per day to the IGS by the 1600 UTC deadline, and contributes the full suite of ultra-rapid products (post-processed and predicted orbit/clock estimates for the GPS satellites; ERPs) four times per day by the pertinent IGS deadlines.

USNO has also coordinated IGS troposphere activities since 2011, producing the IGS Final Troposphere Estimates and chairing the IGS Troposphere Working Group (IGS TWG).

The USNO AC is hosted in the GPS Analysis Division (GPSAD) of the USNO Earth Orientation Department. USNO AC activities, chairing the IGS TWG, and serving on the IGS Governing Board are overseen by Dr. Sharyl Byram who also oversees production of the IGS Final Troposphere Estimates. All GPSAD members, including Dr. Victor Slabinski, Mr. Jeffrey Tracey, and contractor Mr. James Rohde, participate in AC efforts.

USNO AC products are computed using Bernese GNSS Software (Dach et al. 2015)[1]. Rapid products are generated using a combination of network solutions and precise point positioning (PPP; Zumberge et al. (1997)). Ultra-rapid products are generated using network solutions. IGS Final Troposphere Estimates are generated using PPP.

[1]Prior to 2009, the rapid products were computed using Jet Propulsion Laboratory (JPL) GPS Inferred Positioning System (GIPSY) (Webb and Zumberge 1997).

GPSAD also generates a UT1-UTC-like value, UTGPS, five times per day. UTGPS is a GPS-based extrapolation of VLBI-based UT1-UTC measurements. The IERS[2] Rapid Combination/Prediction Service uses UTGPS to improve post-processed and predicted estimates of UT1-UTC. Mr. Tracey oversees UTGPS.

USNO rapid, ultra-rapid and UTGPS products can be downloaded immediately after computation from http://www.usno.navy.mil/USNO/earth-orientation/gps-products. IGS Final Troposphere Estimates can be downloaded at ftp://cddis.gsfc.nasa.gov/gps/products/troposphere/zpd.

2 Product Performance, 2017

Figures 1-4 show the 2017 performance of USNO rapid and ultra-rapid GPS products, with summary statistics given in Table 1. USNO rapid orbits had a median weighted RMS (WRMS) of 16 mm with respect to (wrt) the IGS rapid combined orbits. The USNO ultra-rapid orbits had median WRMSs of 21 mm (24-h post-processed segment) and 38 mm (6-h predict) wrt the IGS rapid combined orbits. These values are slightly improved compared to the 2016 values (18, 26 and 41 mm.

USNO rapid (post-processed) and ultra-rapid 6-h predicted clocks had median 142 ps and 967 ps RMSs wrt IGS combined rapid clocks. Both show slight improvement from the 2016 values of 152 ps and 1216 ps respectively.

USNO rapid polar motion estimates had (x, y) 34 and 28 microarcsec RMS differences wrt IGS rapid combined values. USNO ultra-rapid polar motion estimates differed (RMS; x, y) from IGS rapid combined values by 240 and 222 microarcsec for the 24-h post-processed segment. The USNO ultra-rapid 24-h predict-segment values differed (RMS; x, y) from the IGS rapid combined values by 413 and 370 microarcsec. The rapid polar motion values show significant improvement from 2016 of (x, y) values of 111 and 74 microarcsec.

The USNO AC began using measurements from the Russian GLONASS satellites into processing in 2011 (Byram and Hackman 2012a, b) and has been computing a full set of test rapid and ultra-rapid combined GPS+GLONASS products since 2012.

In 2017, seven-parameter Helmert transformations computed between USNO and IGS ultra-rapid GPS+GLONASS orbits had median RMSs of 37 and 68 mm for the 24-h post-processed and 6-h predict portions, respectively. Meanwhile, the USNO GPS+GLONASS ultra-rapid 24-h post-processed polar motion x and y values differed from the IGS rapid combined values, RMS, by 279 and 194 microarcsec, respectively. USNO GPS+GLONASS ultra-rapid 24-h predicted polar motion x and y values differed from the IGR values, RMS, by 462 and 342 microarcsec, respectively. These data are shown in Table 2/Figures 5-6.

[2]International Earth Rotation and Reference Systems Service

3 USNO AC Conference Presentations/Publications

USNO AC members presentations/publications are as follows for 2017:

S. Byram, “IGS Final Troposphere Product Update”. 2017 IGS Workshop, Paris, France, 2017.

S. Byram, J. Tracey, V. Slabinski, and J. Rohde, âĂIJUSNO Analysis Center UpdateâĂİ. 2017 IGS Workshop, Paris, France, 2017.

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Byram S., and C. Hackman High-Precision GNSS Orbit, Clock and EOP Estimation at the United States Naval Observatory. Proc. 2012 IEEE/ION Position Location and Navigation Symposium, 659-63, 2012b.

Dach, R., S. Lutz, P. Walser, and P. Fridez. (eds.) Bernese GNSS Software Version 5.2. (user manual) Astronomical Institute of University of Bern, Bern, Switzerland, 2015.

Webb F.H. and J.F. Zumberge (eds.) An Introduction to GIPSY/OASIS-II: Precision Software for the Analysis of Data from the Global Positioning System. JPL internal publication D-11088, Jet Propulsion Laboratory, Pasadena, California, 1997.

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Table 1: Precision of USNO Rapid and Ultra-Rapid Products, 2016. All statistics computed with respect to IGS Combined Rapid Products.

USNO GPS satellite orbits				USNO GPS–based polar motion estimates						USNO GPS–based clock estimates	
Statistic: median weighted RMS difference units: mm				Statistic: RMS difference units: 10^{-6} arc sec						Statistic: median RMS difference units: ps	
dates	rapid	ultra–rapid		rapid		ultra–rapid				rapid	ultra–rapid
		past 24 h	6-h predict			past 24 4		24-h predict		past 24 h	6-h predict
				x	y	x	y	x	y		
1/1/2017–12/31/2017	16	21	38	34	28	240	222	413	370	142	967

Table 2: Precision of USNO Ultra-Rapid GPS+GLONASS Test Products, 2016. Orbit statistics computed with respect to IGV Combined Ultra-Rapid GPS+GLONASS Products. Polar motion statistics computed with respect to IGS Rapid combined values.

USNO GLONASS satellite orbits			USNO GPS+GLONASS polar motion estimates	
Median RMS of 7-parameter Helmert transformation units: mm			RMS difference units: 10^{-6} arc sec	
dates	past 24 h	6-h predict	past 24 h	pred 6 h
1/1/2017–12/31/2017	37	68	x: 279 y: 194	x: 462 y: 342

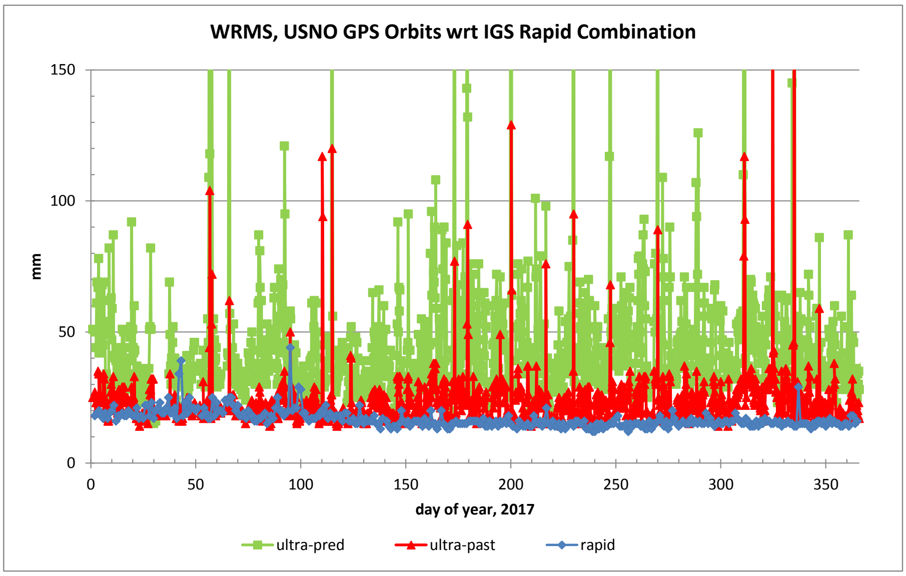

Figure 1: Weighted RMS of USNO GPS orbit estimates with respect to IGS Rapid Combination, 2017. Ültra-pastïrefers to 24-hour post-processed section of USNO ultra-rapid orbits. Ültra-predïrefers to first six hours of ultra-rapid orbit prediction.

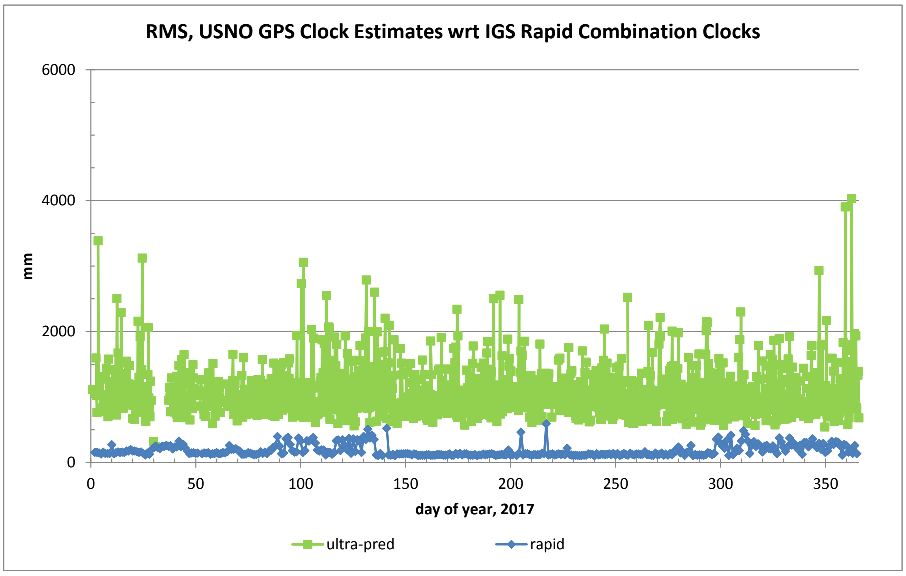

Figure 2: RMS of USNO GPS rapid clock estimates and ultra-rapid clock predictions with respect to IGS Rapid Combination, 2017.

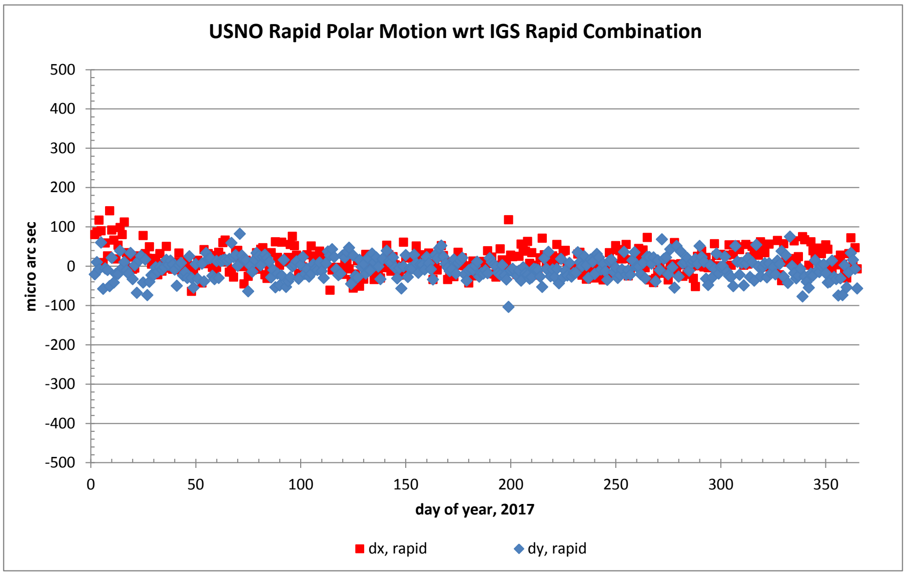

Figure 3: USNO rapid polar motion estimates minus IGS Rapid Combination values, 2017. Note, scale kept same as in previous reports.

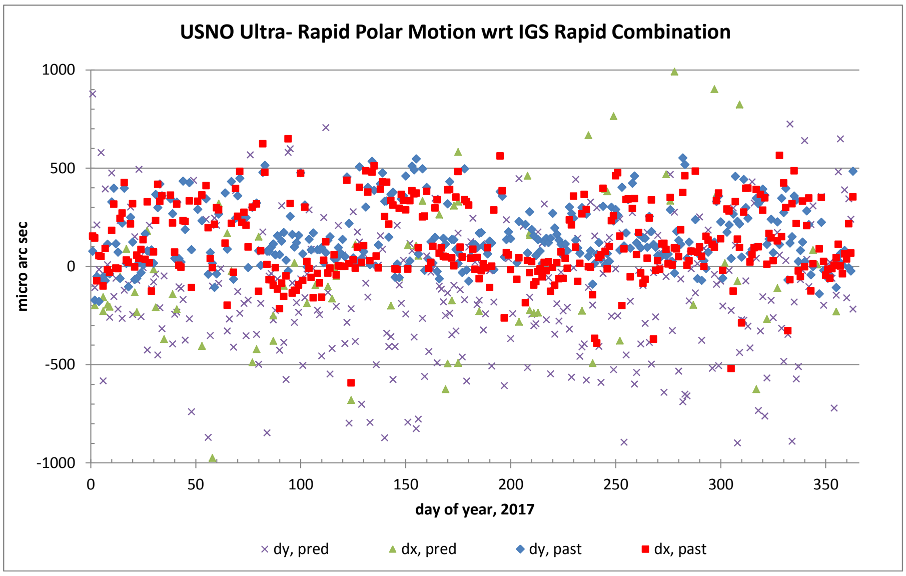

Figure 4: USNO ultra-rapid polar motion estimates minus IGS Rapid Combination values, 2017.

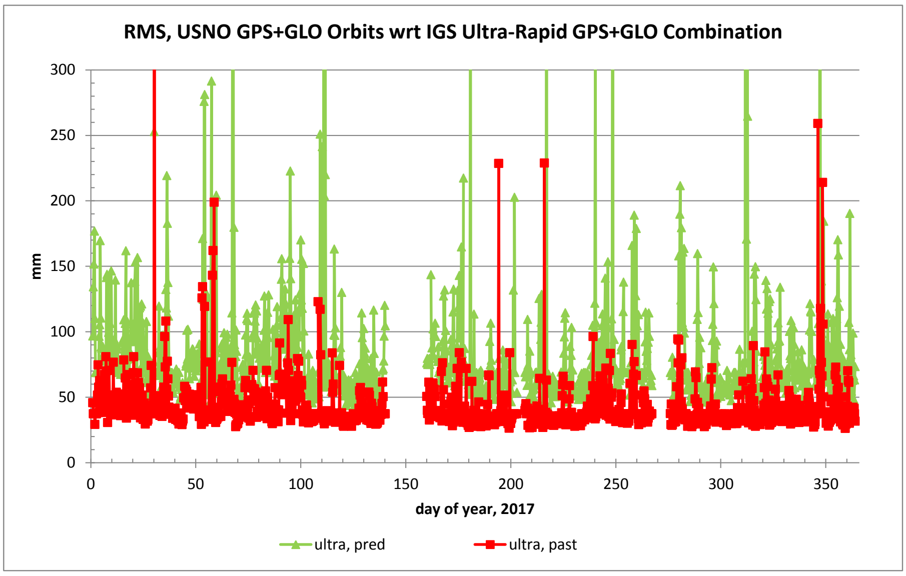

Figure 5: RMS of USNO ultra-rapid GLONASS orbit estimates with respect to IGS Combined Ultra-rapid GLONASS orbits, 2017. "Ultra, past" refers to 24-hour post-processed section of USNO ultra-rapid orbits. "Ultra, pred" refers to first six hours of ultra-rapid orbit prediction.

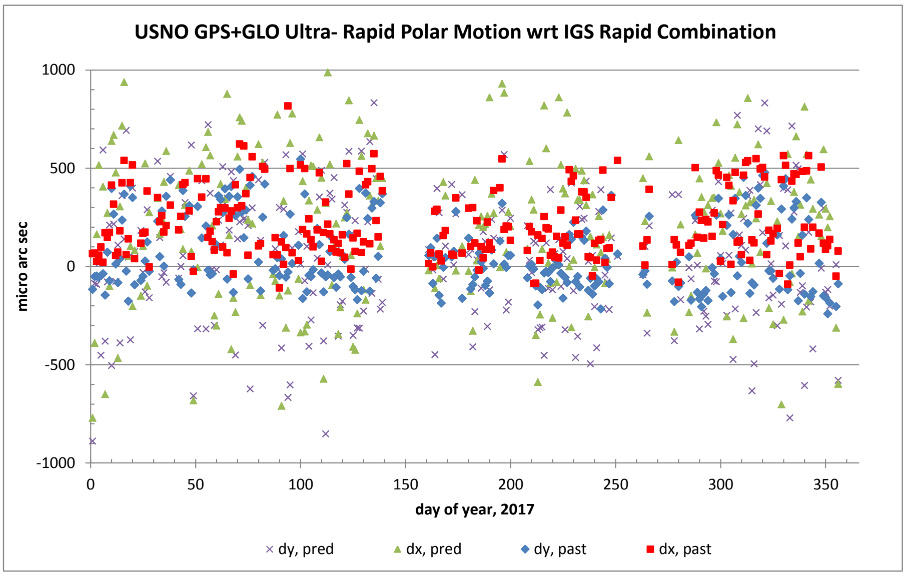

Figure 6: Difference between 24-h post-processed polar motion estimates in USNO test ultra-rapid GPS+GLONASS solution and IGS âĂIJIGRâĂİ GPS-only rapid solution, 2017.

WHU Analysis Center Technical Report 2017

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1 Introduction

The IGS Analysis Center of Wuhan University (WHU) has contributed to the International GNSS Service (IGS) since 2012 with a regular determination of the precise GPS+GLONASS ultra–rapid and rapid products. All the products are generated with the latest developed version of the Positioning And Navigation Data Analyst (PANDA) Software (Liu and Ge 2003; Shi et al. 2008).

During 2017, the standard rapid product generation was continued with minor changes in the software PANDA, and 1-hour and 3-hours updates ultra-rapid products have been released by WHU. In this report we give a summary of the IGS related activities at WHU during the year 2017.

2 WHU Analysis Products

The list of products provided by WHU is summarized in Table 1.

3 Rapid product Changes and Highlights

The main changes in our processing in 2017 were the following:

- switch from IGS08/igs08.atx to IGS14/igs14.atx
- Upgrade of the station list of rapid products
- Estimate the inter-frequency bias of the GPS+GLONASS combined solutions

Table 1: List of products provided by WHU.

	WHU rapid GNSS products
whuWWWD.sp3	Orbits for GPS/GLONASS satellites
whuWWWD.clk	5-min clocks for stations and GPS/GLONASS satellites
whuWWWD.erp	ERPs
	WHU ultra-rapid GNSS products
whuWWWD_HH.sp3	Orbits for GPS/GLONASS satellites provided to IGS every 6 hours
whuWWWD_HH.erp	observed and predicted ERPs provided to IGS every 6 hours

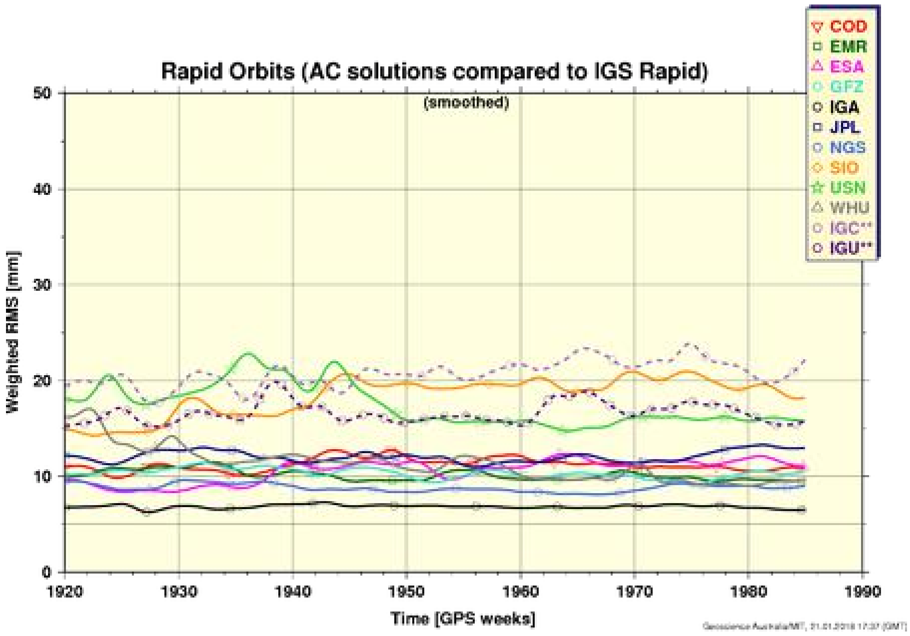

Figure 1: Smoothed WRMS of Rapid orbits.

- Upgrade to GPT2W troposphere models (Böhm et al. 2015)
- Some minor modifications were made in the PANDA software

Due to the updates of data processing strategies and PANDA software, the performance of rapid products from WHU is significantly improved. The main highlight of the rapid products is that they are one of the best products available from the individual IGS analysis centers (Figure 1).

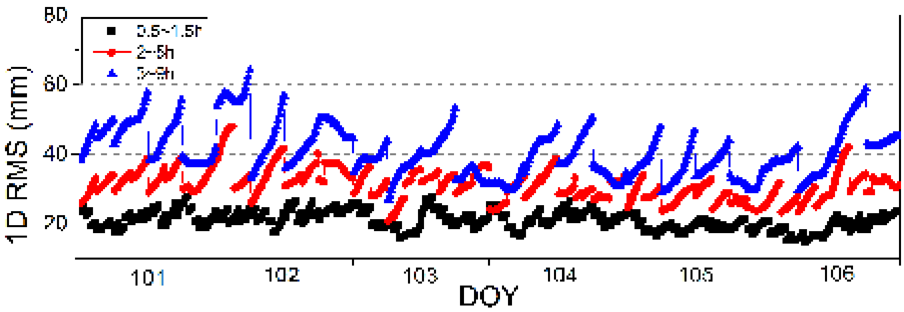

Figure 2: The precision of 1-hour, 3-hour and 9-hour updates of GPS orbit compared with IGS rapid products.

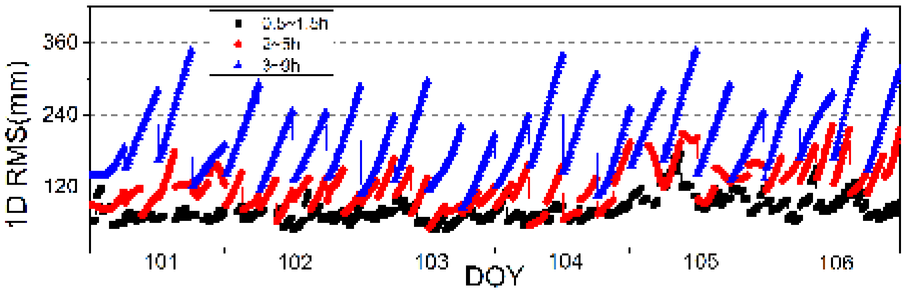

Figure 3: The precision of 1-hour, 3-hour and 9-hour updates of BDS orbit compared with WHU rapid products.

4 1-hour and 3-hour updates ultra-rapid products

The IGS ultra-rapid products are released four times per day, at 03:00, 09:00, 15:00, and 21:00 UTC. At the time of release, these observed products have an initial latency of 3 hr, so the predictions between about 3 and 9 hour are relevant for true real-time uses (Ray and Griffiths. 2008). While, with the increase of the predicted time, the accuracy of the products for real-time uses will be significantly reduced (Figure 2). From the beginning of June 2017, WHU release ultra-rapid products updated every 1-hour and 3-hour (`ftp://igs.gnsswhu.cn/pub/whu/MGEX/`). The ultra-rapid products include GPS/GLONASS/BDS/Galileo satellite orbits, satellite clocks, and Earth Rotation Parameters for a sliding 48-hr period, and the beginning/ending epochs are continuously shifted by 1-hour or 3-hours with each update. The faster updates and shorter latency should lead to significantly improved orbit predictions and reduced errors for user applications (Figure 2 and Figure 3).

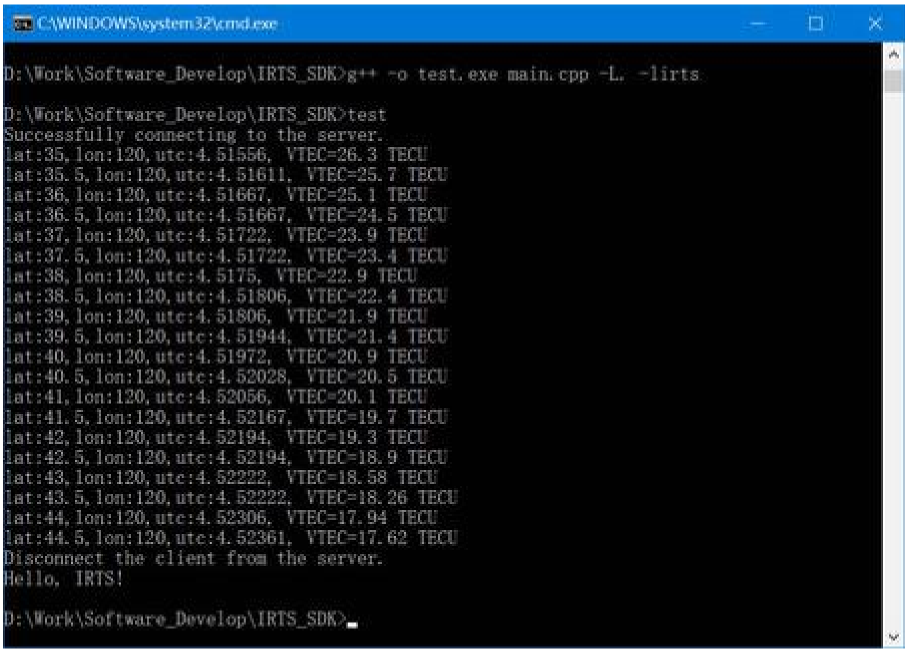

Figure 4: A simple application using IRTS SDK.

5 Ionosphere Activities

WHU joined IGS Ionosphere Working Group as an Ionosphere Associate Analysis Center in 2016. WHU rapid and final ionosphere products (labelled whrg and whug) could be downloaded via CDDIS FTP since 2017.

All WHU ionosphere products including real-time GIMs, rapid GIMs, hourly GIMs and final GIMs are available to the public via FTP (`ftp://pub.ionosphere.cn`). Also, WHU forecasting products (labelled w1pg and w2pg) could be downloaded via the same FTP in the near future. Moreover, a real-time cloud service platform is built and provides real-time ionospheric TEC values for GNSS positioning. The service decouples the algorithm of ionospheric modeling and user terminals. Users only need to receive the ionospheric TEC from the server instead of the coefficients of the ionospheric model. It reduces the complexity and promotes the uniformity of data processing of receiver chip. The corresponding software development kit (called IRTS SDK) can be downloaded from FTP (`ftp://pub.ionosphere.cn/software/IRTS_SDK/`). The SDK supports almost all operating systems and devices, e.g. Windows, Linux, Android, Mac OS, and other devices based on ARM processors (raspberry Pi). Figure 4 presents a simple application using IRTS SDK to receive the ionospheric VTEC from the cloud service platform.

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EUREF Permanent Network Technical Report 2017

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1 Introduction

The International Association of Geodesy Regional Reference Frame sub-commission for Europe, EUREF, defines, maintains, and provides access to the European Terrestrial Reference System (ETRS89). This is done through the EUREF Permanent GNSS Network (EPN). EPN observation data as well as the precise coordinates and the zenith total delay (ZTD) parameters of all EPN stations are publicly available. The EPN cooperates closely with the International GNSS Service (IGS); EUREF members are e.g. involved in the IGS Governing Board, the IGS Reference Frame Working Group, the RINEX Working Group, the IGS Real-Time Working Group, the IGS Antenna Working Group, the IGS Troposphere Working Group, the IGS Infrastructure Committee, and the IGS Multi-GNSS Working Group and Multi-GNSS Extension Pilot Project (MGEX).

This paper gives an overview of the main changes in the EPN during the year 2017. Special attention is given to the EPN Analysis Centres (AC) Workshop held in Brussels in October 2017. Moreover, it should be noted that the EUREF Technical Working Group (TWG) has been renamed into EUREF Governing Board (GB).

2 New EPN CB web site and monitoring

In 2017, the EPN Central Bureau (CB, located at the Royal Observatory of Belgium) improved its tools to monitor the EPN data flow, finished the software to create monthly multi-GNSS skyplots based on daily data files in both the RINEX 2 and 3 formats, and finished running the G-nut/Anubis (Václavovic and Dousa 2016) data quality checks on all its historical EPN data (see Figure 1). All these results are available from the EPN CB web site (Bruyninx et al. 2017).

The on-line ETRS89/ITRS transformation tool was upgraded to include transformations from and to ETRF2000, ETRF2005, ETRF2014, and ITRF2014.

Together with the metadata of the EPN densification network (see http://epncb.eu/_densification/), the EPN CB now maintains and distributes centrally the metadata of 1630 European GNSS stations. In order to deal with the growing metadata complexity, the CB is developing a new system to manage the GNSS station metadata. The "Metadata Management and Dissemination System for Multiple GNSS Networks" (M^3G) and its demo version (Fabian et al. 2017) has been used already during the demonstration phase of the "European Plate Observing System" (EPOS, Fernandes et al. (2017)). Even if originally developed in the frame of EPOS, M^3G will, from 2018 on, also be used within EUREF because of its additional functionalities (such as the export of the new GNSS metadata format GeodesyML). GeodesyML is an extension of the Geography Markup Language (GML) also known as ISO 19136 (the XML structure set forward by the OCG (Open Geospatial Consortium) to exchange geographical information).

The EPN CB updated its web and ftp site to incorporate information on the new IGS14 reference frame as well as revised antenna calibration models. This includes also an update of the individual antenna calibration file ftp://epncb.oma.be/pub/station/general/epnc_14.atx. Compared to epnc_08.atx, one calibration was removed because the calibration facility was not recognized by the IGS, 8 new calibrations were added (7 robot and 1 chamber), and 4 robot calibrations were replaced by chamber calibrations. The EPN CB now makes available 234 individual antenna calibrations (see ftp://epncb.eu/ftp/station/general/indiv_calibrations/ and ftp://epncb.eu/station/densification/indiv_calibrations/), from which 31 are chamber calibrations with Galileo frequencies.

3 Multi-GNSS Tracking Network

27 new stations were integrated in the EPN network in 2017: one in Germany, one in Spain, 11 in Finland, 10 in Great-Britain, one in Portugal and three in Ukraine (see Figure 2). The total number of EPN stations is now 321. Twenty of these new stations provide also GNSS observations in real-time. All stations track GPS and Glonass satellites and 13 out

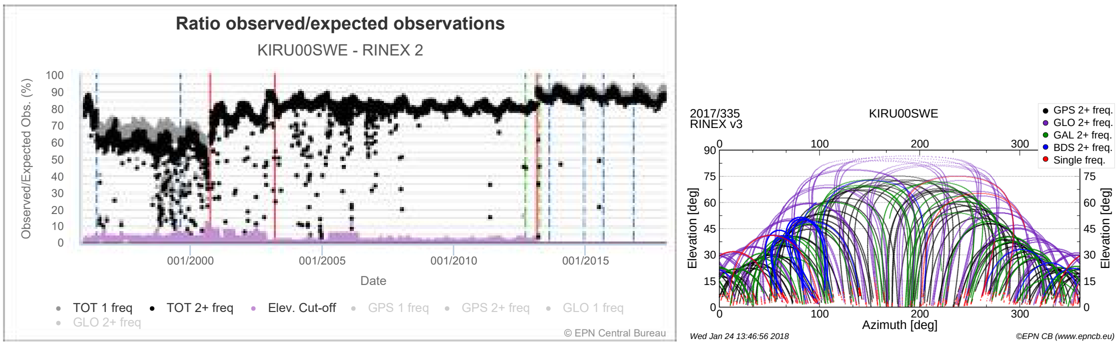

Figure 1: New GNSS data quality plots at the EPN CB. Left: Time series of single and dual frequency tracking. Right: Azimuth/elevation of tracked satellites. Single frequency observations are indicated in red.

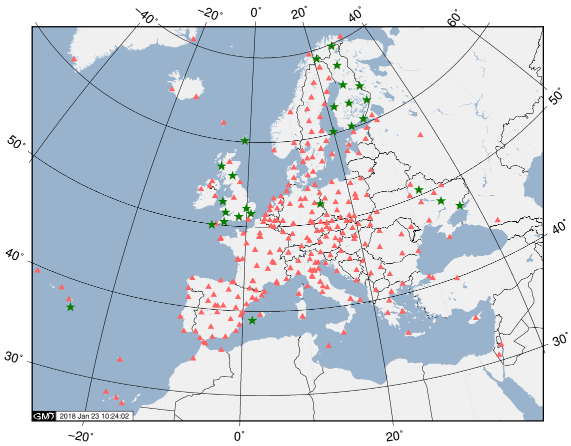

Figure 2: EPN tracking stations, status December 2017. * indicates new stations included in the network in 2017

of them track in addition the European Galileo and Chinese Beidou satellites (Table 1). The majority of the new EPN stations has individual antenna calibrations which are based on GPS and GLONASS signals. Calibrations for Galileo signals are yet not widely available. Only some chamber calibrations are available (Bruyninx and Legrand 2017).

End of 2017, 91% of the EPN stations provided GPS+GLONASS data and 47% Galileo data. About 159 stations provided their data in the RINEX 3 format and 135 of them were using the new RINEX 3 file naming conventions. In Oct. 2017, 56% of the stations that were providing RINEX 3 data, used the 3.02 format. The remaining were already using 3.03. The EUREF GB discussed the usefulness of RINEX 3 to RINEX 2 conversion. This could be important for the future if parallel transfer of RINEX 3 and RINEX 2 file might not be possible for all stations. However, for new or extended constellations such conversion could be quite complicated.

Table 1: New stations included in the EPN in 2016 (stations indicated with * also contribute to the IGS)

4–char ID	Location	Tracked Satellite Systems	Real–time	Antenna Calibration
ADAR00GBR	Aberdaron	GPS GLO	RT	Individual (GEO++)
ARIS00GBR	Arisaig	GPS GLO	RT	Individual (GEO++)
CHIO00GBR	Chilbolton	GPS GLO		Individual (GEO++)
DNMU00UKR	Dnipro	GPS GLO		Type mean
EDIN00GBR	Edinburgh	GPS GLO	RT	Type mean
FINS00FIN	Finstrom	GPS GLO GAL BDS SBAS	RT	Individual (GEO++)
IBIZ00ESP	Ibiza	GPS GLO GAL BDS		Type mean
JOE200FIN	Joensuu	GPS GLO GAL BDS SBAS	RT	Individual (GEO++)
KEV200FIN	Utsjoki	GPS GLO GAL BDS SBAS	RT	Individual (GEO++)
KILP00FIN	Kilpisjarvi	GPS GLO GAL BDS SBAS	RT	Individual (GEO++)
KIV200FIN	Aanekoski	GPS GLO GAL BDS SBAS	RT	Individual (GEO++)
LDB200DEU	Lindenberg	GPS GLO GAL BDS SBAS		Individual (GEO++)
LERI00GBR	Lerwick	GPS GLO	RT	Individual (GEO++)
MARP00UKR	Mariupol	GPS GLO		Type mean
MET300FIN*	Kirkkonummi	GPS GLO GAL BDS SBAS	RT	Individual (GEO++)
OUL200FIN	Oulu	GPS GLO GAL BDS SBAS	RT	Individual (GEO++)
PMTH00GBR	Plymouth	GPS GLO	RT	Type mean
PRYL00UKR	Pryluky	GPS GLO		Type mean
RAEG00PRT*	Sao Pedro	GPS GLO		Type mean
ROM200FIN	Kuhmo	GPS GLO GAL BDS SBAS	RT	Individual (GEO++)
SCIL00GBR	Hugh Town	GPS GLO	RT	Type mean
SHOE00GBR	Shoeburyness	GPS GLO	RT	Type mean
SNEO00GBR	St Neots	GPS GLO	RT	Individual (GEO++)
SOD300FIN	Sodankyla	GPS GLO GAL BDS SBAS	RT	Individual (GEO++)
SWAS00GBR	Swansea	GPS GLO	RT	Individual (GEO++)
VAA200FIN	Vaasa	GPS GLO GAL BDS SBAS	RT	Individual (GEO++)
VIR200FIN	Virolahti	GPS GLO GAL BDS SBAS	RT	Individual (GEO++)

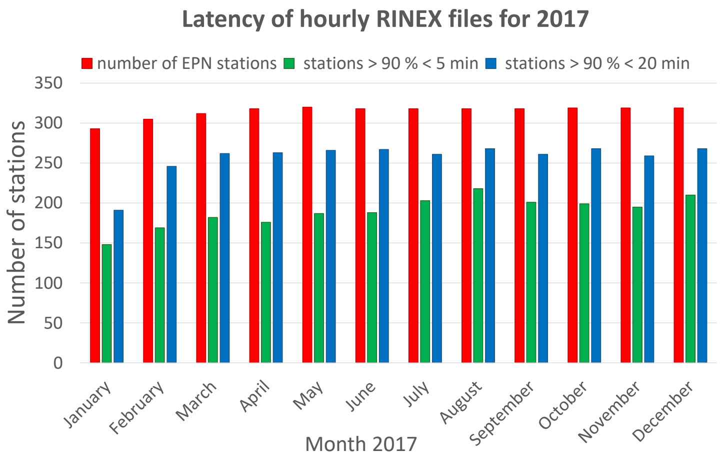

Figure 3: Hourly data latency of EPN stations.

4 Data Centres

At the end of 2017, the contract between the Austrian Academy of Sciences (AAS) and the Federal Office of Metrology and Surveying (BEV) for maintaining the EPN data center "OLG" expired. To continue the long tradition of contributing to EUREF, it was decided to migrate the OLG data center to the BEV. Embedded in the BEV IT-Infrastructure, using revisited scripts, and an adapted data storage system, the new EPN data center "BEV" aims at a higher level of security and availability. Compared to the old (OLG) server, the BEV data structure at the ftp-server was changed to be similar to the other EPN regional data center at BKG. Files can be uploaded as "anonymous", which means that no registration is needed. After several internal file checks the uploaded files are presented. A requirement is that the files are from official EPN stations and are true RINEX files, otherwise the files are deleted immediately. To monitor the data flow on the new server, BEV stores all its log files in a new database system called "elasticsearch". It allows to easily help customers when there are problems with file uploads and identify the origin of the problem. The transition from OLG to BEV was completed in June 2017. Since then, the monthly monitoring of the hourly RINEX files of the EPN data centres at BKG and BEV/OLG shows a significant improvement in terms of latency reduction (Figure 3). The new "BEV" data center is now available at ftp://gnss.bev.gv.at/.

5 Data Analysis

5.1 Positions

The EPN ACs routinely process GNSS observations collected at EPN stations. In 2017, all 16 ACs (Table 2) were providing final weekly and daily coordinate solutions of their subnetworks, 10 ACs were providing also rapid daily solutions, and 3 ACs were providing ultra-rapid solutions.

Since January 29, 2017 (GPS week 1934), to be consistent with IGS products, the EPN ACs started to use the IGS14/epn_14.atx framework during GNSS data analysis. In August (GPS week 1962), the OLG AC stopped its activities as EPN AC. Its tasks were taken over by the new EPN AC – BEV, operated by the Federal Office of Metrology and Surveying, Austria. In December (week 1980), MUT AC changed the processing software from Bernese GNSS Software 5.2 to GAMIT/GLOBK software.

At the EUREF AC workshop, held in Brussels (October 25-26, 2017), it was also recommended that more ACs start submitting rapid products, so that all EPN stations are processed and monitored. Alternatively, ACs already submitting rapid solutions were asked to consider adding more EPN stations to their rapid subnetworks, so that all EPN stations could be included in rapid combined solutions.

At the workshop, also the experiences with Galileo data processing were presented by several EPN ACs (BEK, BKG, and ROB). The possibility to use Galileo observations in operational EPN products was discussed. However, because of a small number of available receiver antenna calibrations for Galileo observations, it was decided to wait with the inclusion of Galileo in operational EPN analysis. Nevertheless, all ACs were encouraged to make further tests using Galileo observations.

The Analysis Combination Centre (ACC) continued to combine the AC's subnetwork coordinate solutions (provided in SINEX format) into official EPN solutions. Since week 1934, all EPN combined coordinate solutions are aligned to the latest IGS reference frame – IGS14.

As a consequence of changing the method for creating weekly combined EPN solutions in 2016 (EPN LAC mail 2134), the reports published on the EPN ACC website (http://www.epnacc.wat.edu.pl/solutions/weekly.html) were modified. Detailed reports for individual daily AC's solutions contain now the coordinate consistency with respect to the daily combined solutions for each station and day of the last combined week. The consistency of the weekly combined coordinates with respect to the IGS reference frame (currently IGS14) is also provided interactively for each station on this website.

Table 2: EPN Analysis Centres characteristics: provided solutions (W – final weekly, D – final daily, R – rapid daily, U – ultra-rapid), the number of analyzed GNSS stations (in brackets: stations added in 2017), used software (GOA – GIPSY-OASIS, BSW – Bernese GNSS Software), used GNSS observations (G – GPS, R – GLONASS, E – Galileo, C – BeiDou)

AC	Analysis Centre Description	Solutions	# sites	Software	GNSS
ASI	Centro di Geodesia Spaziale G. Colombo, Italy	WDRU	53(3)	GOA 6.2	G
BEK	Bavarian Academy of Sciences & Humanities, Germany	WDR	97(2)	BSW 5.2	GR
BEV[1]	Federal Office of Metrology and Surveying, Austria	WD	101(101)	BSW 5.2	GR
BKG	Bundesamt für Kartographie und Geodäsie, Germany	WDRU	117(8)	BSW 5.2	GR
COE	Center for Orbit Determination in Europe, Switzerland	WD	43(0)	BSW 5.3	GR
IGE	Instituto Geografico Nacional, Spain	WDR	86(12)	BSW 5.2	GR
IGN	Institut Geographique National, France	WDR	64(0)	BSW 5.2	G
LPT	Federal Office of Topography swisstopo, Switzerland	WDRU	60(1)	BSW 5.3	GREC
MUT	Military University of Technology, Poland	WD	144(7)	BSW 5.2	GR
NKG	Nordic Geodetic Commission, Lantmateriet, Sweden	WD	88(12)	BSW 5.2	GR
OLG	Austrian Academy of Science, Austria	WD	101(3)	BSW 5.2	G
RGA	Republic Geodetic Authority, Serbia	WD	56(0)	BSW 5.2	GR
ROB	Royal Observatory of Belgium, Belgium	WDR	98(14)	BSW 5.2	GR
SGO	BFKH Satellite Geodetic Observatory, Hungary	WDR	42(0)	BSW 5.2	GR
SUT	Slovak University of Technology, Slovakia	WD	59(3)	BSW 5.2	GR
UPA	University of Padova, Italy	WDR	57(8)	BSW 5.2	GR
WUT	Warsaw University of Technology, Poland	WDR	119(13)	BSW 5.2	GR

5.2 Troposphere

Besides station coordinates, the 16 ACs also submit ZTD parameters on a routine basis in the SINEX_TRO format. Fourteen ACs are also submitting horizontal gradients. The ZTDs and horizontal gradients are delivered with a sampling rate of one hour, on a weekly basis, but in daily files. As regard to the troposphere mapping function, eight of the 16 ACs use the Vienna Mapping Function (VMF1), and the remaining eight the Global Mapping Function. At the EPN Analysis Centres Workshop in Brussels, the harmonization of the troposphere modelling among the EPN ACs was proposed in order to increase the consistency between AC solutions. It was agreed that from GPS week 1980 onwards it would be mandatory to model the tropospheric delay using the VMF1 mapping function together with a priori hydrostatic delays from VMF1 grids (based on atmospheric pressure data from ECMWF[2]).

In 2017, the ZTD estimates are provided for 310 stations by three or more ACs (compared to 280 in 2016), for 10 stations by two, and for 6 stations just by one AC.

http://epncb.eu/_productsservices/sitezenithpathdelays/ shows the weekly mean bias (top) and the related standard deviation (bottom). They give insight into the agree-

[2]European Centre for Medium-range Weather Forecasting

ment of the individual solutions with respect to the combined solution. The time series are based on EPN-Repro2 solutions (GPS week 834 until 1824) and on operational solutions afterwards.

The EPN multi-year tropospheric solution has been updated twice: in April, till GPS week 1934, and October, till GPS week 1963. For each EPN station ZTD time series, ZTD monthly mean and comparison with radiosonde data (if collocated) plots are available at the EPN CB.

5.3 Reprocessing

The EPN-Reprocessing activities have been finalized in 2016 and provided a homogeneous set of coordinates for the time period between 1996 and 2013 in the IGb08. Apparently it became clear that there exists a small inconsistency between the reprocessed coordinates and the operational data that have been processed thereafter. While for the EPN-reprocessing results from five ACs were provided using BSW 5.2 (3), GAMIT 10.5 (1) and GOA 6.2 (1) that were combined, the operational data are a combination of 16 ACs using BSW 5.2 (14), GAMIT 10.5 (1) and GOA 6.2 (1). Investigations are still not concluded, but the outcome will have to be considered for future reprocessing campaigns. During the last AC workshop in Brussels it was decided to postpone the next reprocessing campaign until newly reprocessed orbits and Earth Orientation Parameters for the period 1996 and 2017 are available in the IGS14. This might still take a few years.

In parallel, a tropospheric combined solution for the period 1996-2014 has been computed (Pacione et al. 2017). For each EPN station, plots on ZTD time series, ZTD monthly means, and a comparison versus Radiosonde data (if collocated), are available at the EPN Central Bureau (`http://epncb.eu/_productsservices/troposphere/`). This EPN-Repro2 tropospheric data set has been used for the assessment of ALARO climate model simulation (Berckmans et al. 2017).

6 Densification of the IGS

An EPN multi-year position and velocity solution is maintained as the densification of the IGS realization of the ITRS in Europe. This solution is computed with the CATREF software (Altamimi et al. 2007) and updated each 15 weeks.

Starting with the release of IGS14 (January 2017, GPS week 1934), the EPN multi-year position and velocity solution is replaced by a new version based on the daily EPN-Repro2 solutions (from GPS week 834 to GPS week 1772) and the daily EPN routine solutions (from GPS weeks 1773 up to present). This solution has a revised discontinuity list and incorporates the ITRF2014 post-seismic deformation models (`ftp://itrf.ign.fr/pub/itrf/itrf2014/ITRF2014-psd-gnss.dat`) for 5 stations: ANKR00TUR, BUCU00ROU,

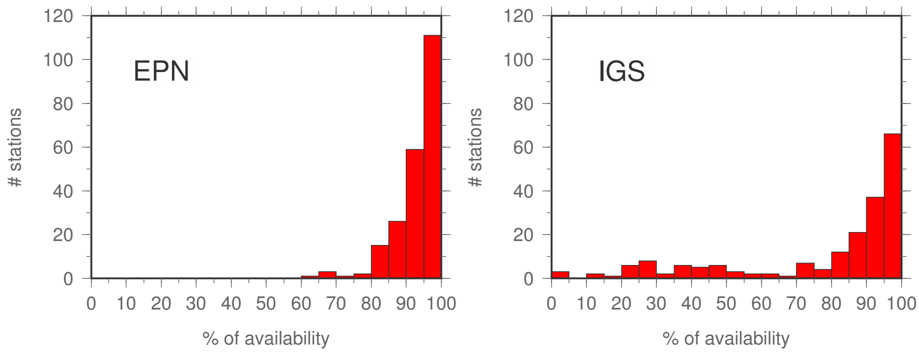

Figure 4: Station availability in the time series (%) in the EPN solution C1950 (left) and the IGS solution IGS17P21 (right) for the 212 common stations with more than 10 weeks of observations in both solutions.

ISTA00TUR, REYK00ISL, TUBI00TUR (see Legrand et al. (2017)). It is consistent with the epn_14.atx ground antenna calibrations and aligned to the IGS14 reference frame. In order to insure the consistency of the daily solutions with the IGS14/epn_14.atx, the positions prior to GPS week 1934 were corrected for the position changes caused by the change from epn_08.atx to epn_14.atx. To maximize the consistency with IGS, when available, the position offsets computed by the IGS for IGS station/antenna pairs were applied. If not available, the latitude-dependent models (IGSMAIL-7399) of the expected position offsets were applied.

The positions and velocities of the EPN multi-year solution C1950 (GPS weeks up to 1950) agree well with the IGS solution for the same GPS week (IGS17P21). Most of the large differences can be explained by a different discontinuity list or different periods of observations (a large data gap or sparse time series affecting the IGS solution). This effect is clearly seen in Figure 4: 33 of the 212 common stations have less than 50% of observations in the IGS analysis while the same stations have more than 80% of data in the EPN analysis.

After rejecting EPN stations with less than 3 years of observations or less than 50% of observation completeness, the rms of the velocity differences of the C1950 wrt the IGS17P21 is 0.19 mm/yr, 0.15 mm/yr, 0.51 mm/yr for resp. the North, East and Up components. For the positions differences (using only stations with the same applied discontinuities), the rms is 1.3 mm for the North, 1.7 mm for the East and 5.6 mm for the Up component.

The EPN multi-year product files (including the discontinuity list and associated residual position time series) are available at `ftp://epncb.eu/pub/station/coord/EPN/`. More details can be found in `http://epncb.eu/_productsservices/coordinates/`. The residual daily position time series and position time series in IGS14 and ETRF2014 are available online at `http://epncb.oma.be/_productsservices/timeseries/`. In addition to the time series of the official product, extended time series are updated every day by adding the recent EPN daily combined solutions not yet included in the final combined EPN solution. Together with the quality check monitoring performed by EPN CB, these quick updates allow to monitor the behavior of the EPN stations and to react promptly in case of problem.

7 Densification of the EPN

EUREF, in the frame of the EPN Densification WG, combines the weekly SINEX solutions provided by European countries for their dense national active GNSS networks. All available weekly solutions are stacked to obtain a consistent cumulative position/velocity product. The combination is performed using the CATREF software. The total number of stations included in the EPN densification exceeds 3400 as of December 2017. The multi-year solution being published will be expressed in IGb08 and will include weekly SINEX files up to GPS week 1933 (Kenyeres et al. 2017).

The densification products will be an essential contribution to several groups and projects as EPOS and the European Positioning System (EUPOS).

8 Stream and Product Dissemination

The number of EPN real-time stations is still on the 50 % level. The introduction of long mount-point names on the three EPN broadcasters has been continued. All 21 new stations from Finland were introduced with long names only. Since it might be necessary for some time to use short and long mount point names in parallel, at the beginning of 2018 an update of the caster software running at the three EPN organisations will facilitate this parallel use.

The number of streams supporting the RTCM 3.3 Multiple Signal Messages (MSM) has been growing. All new Finnish stations are providing MSM. The bandwidth needed for MSM is approx. four times higher than for the legal messages.

The monitoring of the three EPN broadcasters at the EPN CB covers mainly two sections: the availability of data and product streams (http://epncb.eu/_networkdata/data_access/real_time/status.php) and the meta-data and latency checks (http://epncb.eu/_networkdata/data_access/real_time/metadata_monitoring.php). Since there are discrepancies between the actual content of the data streams and the format information given in the source-table, there is an ongoing discussion within the EPN GB whether an automated and centralized update of all source-tables is useful and necessary.

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SIRGAS Regional Network Associate Analysis Centre Technical Report 2016

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1 Introduction

A network of continuously operating GNSS stations distributed over Latin America gives the present realization of SIRGAS. This network is processed on a weekly basis to generate instantaneous weekly station positions aligned to the ITRF and multi-year (cumulative) reference frame solutions. The instantaneous weekly positions are especially useful when strong earthquakes cause co-seismic displacements or strong relaxation motions at the SIRGAS stations disabling the use of previous coordinates. The multi-year solutions provide the most accurate and up-to-date SIRGAS station positions and velocities. They are used for the realization and maintenance of the SIRGAS reference frame between two releases of the ITRF. While a new ITRF release is published more or less every five years, the SIRGAS reference frame multi-year solutions are updated every one or two years.

2 SIRGAS reference network

The SIRGAS continuously operating network is composed of 423 stations (Fig. 1), 17 of which were integrated in 2017. 24% of the SIRGAS stations is also processed by the IGS processing centres. 78% of the stations tracks GLONASS, 13% Galileo and 5% Beidou. The operational performance of the SIRGAS network is based on the contribution of more than 50 organizations, which install and operate the permanent stations and voluntarily provide the tracking data for the weekly processing of the network. Since more and more Latin American countries are qualifying their national reference frames by installing GNSS continuously operating stations and these stations shall be consistently integrated into the continental reference frame, the SIRGAS reference network comprises:

- One core network (SIRGAS-C), primary densification of ITRF in Latin America, with a good continental coverage and stabile site locations to ensure high long-term stability of the reference frame.
- National reference networks (SIRGAS-N) improving the densification of the core network and providing accessibility to the reference frame at national and local levels. Both, the core network and the national networks satisfy the same characteristics and quality; and each station is processed by three analysis centres.

3 SIRGAS processing centres

The SIRGAS-C network is processed by DGFI-TUM as IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIRGAS). The SIRGAS-N networks are computed by the SIRGAS Local Processing Centres, which operate under the responsibility of national Latin American organisations. At present, the SIRGAS Local Processing Centres are:

- CEPGE: Centro de Procesamiento de Datos GNSS del Ecuador, Instituto GeogrÃąfico Militar (Ecuador)
- CNPDG-UNA: Centro Nacional de Procesamiento de Datos GNSS, Universidad Nacional (Costa Rica)
- CPAGS-LUZ: Centro de Procesamiento y Análisis GNSS SIRGAS de la Universidad del Zulia (Venezuela)
- IBGE: Instituto Brasileiro de Geografia e Estatistica (Brazil)
- IGAC: Instituto Geográfico Agustín Codazzi (Colombia)
- IGM-Cl: Instituto Geográfico Militar (Chile)
- IGN-Ar: Instituto Geográfico Nacional (Argentina)
- INEGI: Instituto Nacional de Estadística y Geografía (México)
- SGM: Servicio Geográfico Militar (Uruguay)

These processing centres deliver loosely constrained weekly solutions for the SIRGAS-N national networks, which are combined with the SIRGAS-C core network to get homogeneous precision for station positions and velocities. The individual solutions are combined by the SIRGAS Combination Centres currently operated by DGFI-TUM and IBGE.

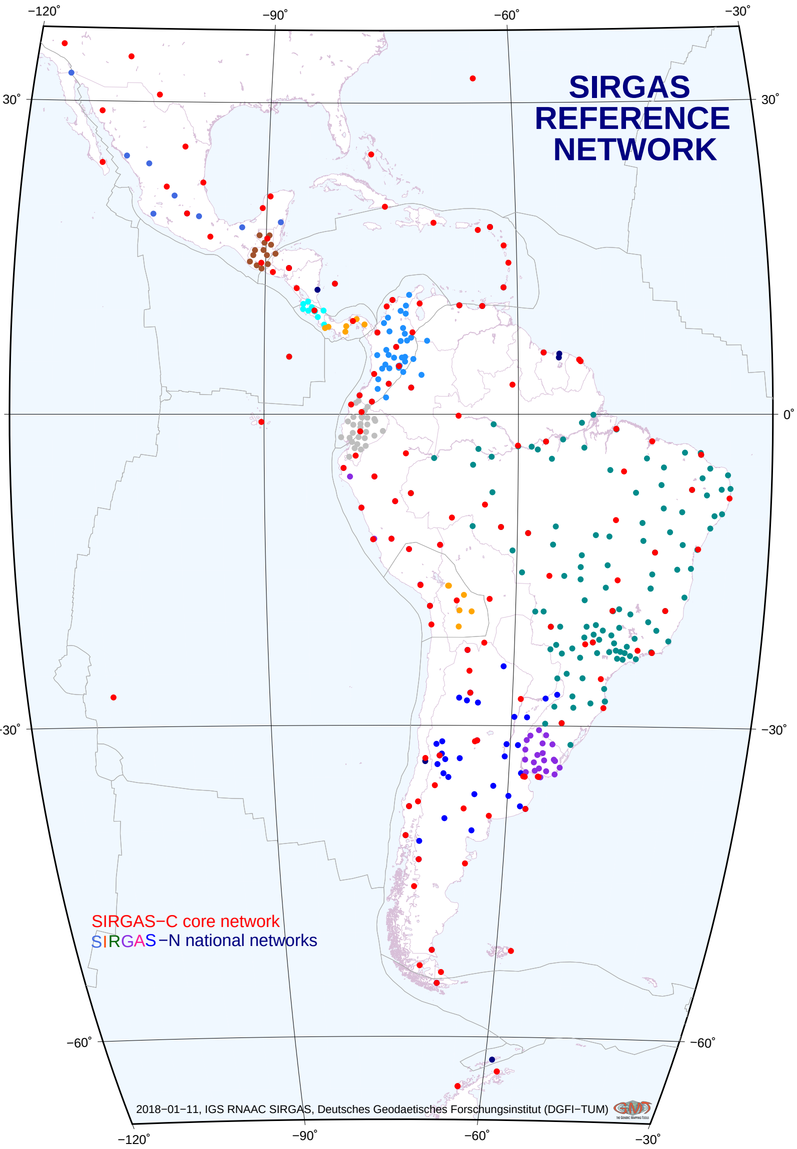

Figure 1: SIRGAS reference network as of January 2018.

4 Routine processing of the SIRGAS reference frame

The SIRGAS processing centres follow unified standards for the computation of the loosely constrained solutions. These standards are generally based on the conventions outlined by the IERS and the GNSS-specific guidelines defined by the IGS; with the exception that in the individual SIRGAS solutions the satellite orbits and clocks as well as the Earth orientation parameters (EOP) are fixed to the final weekly IGS values (SIRGAS does not compute these parameters), and positions for all stations are constrained to ±1 m (to generate the loosely constrained solutions in SINEX format). INEGI (Mexico) and IGN-Ar (Argentina) employ the software GAMIT/GLOBK; the other local processing centres use the Bernese GPS Software V. 5.2. At present, the SIRGAS efforts concentrate on a new reprocessing of the reference network based on the IGS14 reference frame.

5 Kinematics of the SIRGAS reference frame

The kinematics of reference networks is estimated by means of cumulative solutions covering many years of observations. The combined adjustment is done with the program ADDNEQ2 of the Bernese GNSS Software V5.2 and it is based on the loosely constrained weekly solutions (SINEX files) submitted by the IGS RNAAC SIRGAS to the IGS Analysis Centres. The latest SIRGAS multi-year solution, called SIR17P01(Fig.reffig:2), covers the period from April 17, 2011 (GPS week 1632) to January 28, 2017 (GPS week 1933) and includes only weekly solutions referring to the IGS08/IGb08 reference frame. This new SIRGAS cumulative solution has been aligned to the IGS14 reference frame and it is consistent with the igs14.atx ground antenna calibrations. This was achieved by applying corrections to the positions of stations with updated ground antenna calibrations (Fig. 3). When available, the applied corrections were taken from the station-specific estimates published by the IGS; otherwise, they were computed from the latitude-dependent models recommended by the IGS. SIR17P01 includes positions and velocities for 345 SIRGAS stations referring to the IGS14, epoch 2015.0. Its estimated precision is ± 1,2 mm (horizontal) and ±, 2,5 mm (vertical) for the station positions at the reference epoch, and ±0,7 mm/a (horizontal) and ±1,1 mm/a (vertical) for the velocities.

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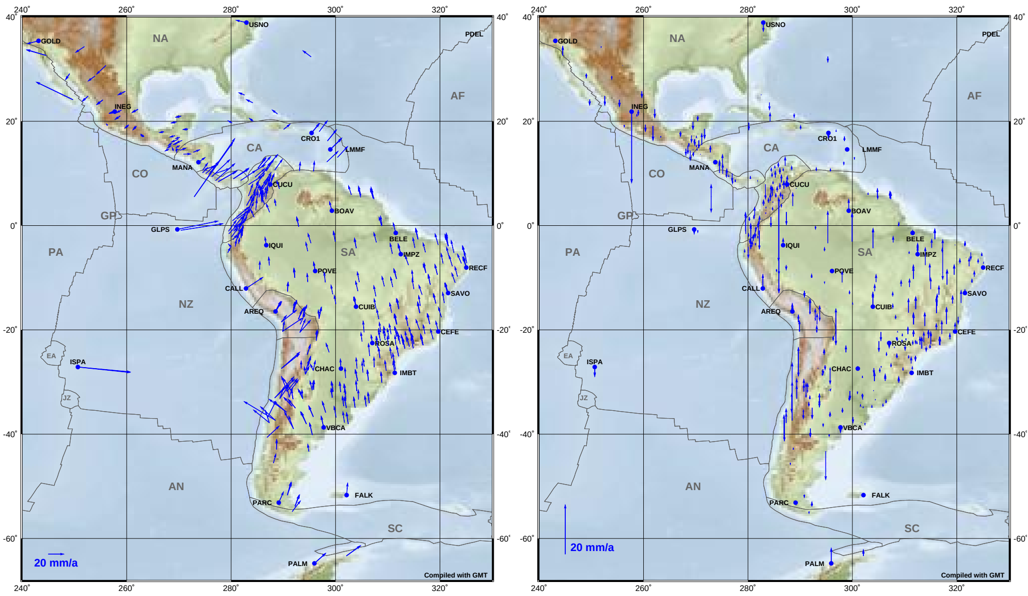

Figure 2: Horizontal (left) and vertical (right) velocities of the SIRGAS multi-year solution SIR17P01. Labels identify reference stations used for the geodetic datum realization.

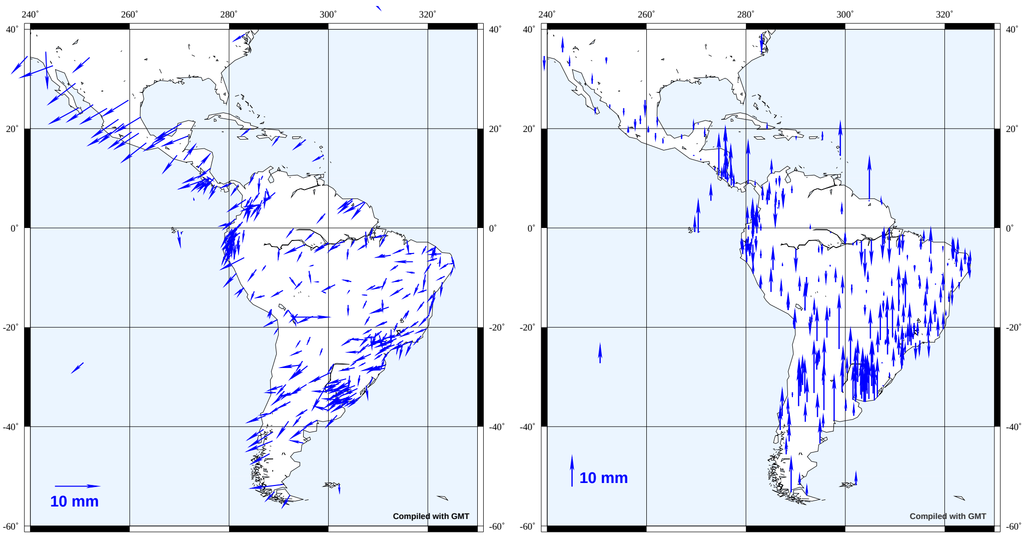

Figure 3: Differences in horizontal (left) and vertical (right) station positions referring to the IGS14 and the IGS08/IGb08 reference frames.

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Part III

Data Centers

Infrastructure Committee Technical Report 2017

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1 Introduction

The IGS Infrastructure Committee (IC) is a permanent body established to ensure that the data requirements for the highest quality GNSS products are fully satisfied while also anticipating future needs and evolving circumstances. Its principal objective is to assure that the IGS infrastructure components that collect and distribute the IGS tracking data and information are sustained to meet the needs of principal users, in particular the IGS analysis centers, fundamental product coordinators, pilot projects, and working groups.

The IC fulfills this objective by coordinating and overseeing facets of the IGS organization involved in the collection and distribution of GNSS observational data and information, including network stations and their configurations (instrumentation, monumentation, communications, etc), and data flow.

The IC establishes policies and guidelines, where appropriate, working in close collaboration with all IGS components, as well as with the various agencies that operate GNSS tracking networks. The IC interacts with International Association of Geodesy (IAG) sister services and projects – including the International Earth Rotation and Reference Systems Service (IERS) and the Global Geodetic Observing System (GGOS) – and with other external groups (such as the RTCM) to synchronize with the global, multi-technique geodetic infrastructure.

Current Members: renewed on Dec, 2017 for terms up to Dec 2019;

- Carine Bruyninx (ROB)
- Lou Estey (UNAVCO)
- Nicholas Brown (GA)
- Nacho Romero – Chairman – (ESOC)

- Brian Donahue (NRCan)
- Wolfgang Soehne (BKG)

Ex–officio Members:

- Steve Fisher – Central Bureau
- David Maggert – Network Coordinator
- Michael Moore – Analysis Coordinator
- Tom Herring – Analysis Coordinator
- Axel Ruelke – Real time Working Group Chair
- Bruno Garayt – Reference Frame Coordinator
- Carey Noll – Data Center Working Group Chair
- Michael Coleman – Clock Products Coordinator

2 Summary of Activities in 2017

Over 2017 the IC has supported the Network Coordinator on answering questions from IGS product and data users, plus;

- Added 31 stations to the Station Network,
- removed 16 long-standing absent stations from the network,
- implemented combined RINEX 3 multi-GNSS mixed navigation file at CDDIS: **BRDC00IGS** files
- created **RX3name** binary command tool application to generate long filenames from short filenames
- Achieved 100% RINEX 3 longname for RINEX 3 capable stations (at CDDIS)

The IC has participated in the 2017 Paris IGS Workshop and supports each of the Working groups as needed in terms of planning station contacts and format development.

The RINEX 3 data file integration into the IGS can be considered complete and successful at this time. Work continues in coordination with the different working groups for all the IGS products to accept the station long names into the products.

3 Activities in 2017

During 2018 the IC will be concentrating on the following recommendations that came from the 2017 IGS Workshop;

1. To implement a Station product participation table for the IGS station webpage to show each station inclusion in the different IGS products
2. To create a way forward to provide at least weekly positions for ALL IGS network stations, rather than just having the stations that Final ACs have selected
3. To investigate and create a plan of what to do with parallel station installation data when upgrading antennas; whether to use the data to estimate the "antenna change" offsets, where to store the parallel data and the results.
4. To support the Antenna WG in the new test activity to check available individual antenna calibrations in the existing IGS stations
5. To request NSWE pictures from station antennas especially for those that do provide individual antenna calibrations
6. To request antenna's ground plane distance to the ground (local height) ($<$ 10cm accuracy)

CDDIS Global Data Center Technical Report 2017

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1 Introduction

The Crustal Dynamics Data Information System (CDDIS) is NASA's data archive and information service supporting the international space geodesy community. For over 35 years, the CDDIS has provided continuous, long term, public access to the data (mainly GNSS-Global Navigation Satellite System, SLR-Satellite Laser Ranging, VLBI-Very Long Baseline Interferometry, and DORIS-Doppler Orbitography and Radiopositioning Integrated by Satellite) and products derived from these data required for a variety of science observations, including the determination of a global terrestrial reference frame and geodetic studies in plate tectonics, earthquake displacements, volcano monitoring, Earth orientation, and atmospheric angular momentum, among others. The specialized nature of the CDDIS lends itself well to enhancement to accommodate diverse data sets and user requirements. The CDDIS is one of NASA's Earth Observing System Data and Information System (EOSDIS) Distributed Active Archive Centers (DAACs); EOSDIS data centers serve a diverse user community and are tasked to provide facilities to search and access science data and products. The CDDIS is also a regular member of the International Council for Science (ICSU) World Data System (WDS) and the Earth Science Information Partners (ESIP).

The CDDIS serves as one of the primary data centers and core components for the geometric services established under the International Association of Geodesy (IAG), an organization that promotes scientific cooperation and research in geodesy on a global scale. The system has supported the International GNSS Service (IGS) as a global data center since 1992. The CDDIS activities within the IGS during 2017 are summarized below; this report also includes any recent changes or enhancements made to the CDDIS.

2 System Description

The CDDIS archive of IGS data and products are accessible worldwide through anonymous ftp (ftp://cddis.nasa.gov). The CDDIS has also implemented web-based access to the archive (https://cddis.nasa.gov/archive). The CDDIS is located at NASA's Goddard Space Flight Center (GSFC) and is available to users 24 hours per day, seven days per week.

The CDDIS computer facility is fully redundant with primary and secondary/failover systems. Since December 2016, the CDDIS utilizes a virtual machine (VM) based system configured with 100 Tbytes of unified storage operating within the EOSDIS computer facility and network infrastructure (see Figure 1). This system configuration provides a reliable/redundant environment (power, HVAC, 24-hour on-site emergency personnel, etc.) and network connectivity; a disaster recovery system is installed in a different location on the GSFC campus for rapid failover when required. This system location has addressed a key operational issue CDDIS experienced over the past several years: the lack of consistent and redundant power and cooling in its computer facility. Furthermore, multiple, redundant 40G network switches are available to take full advantage of a high-performance network infrastructure by utilizing fully redundant network paths for

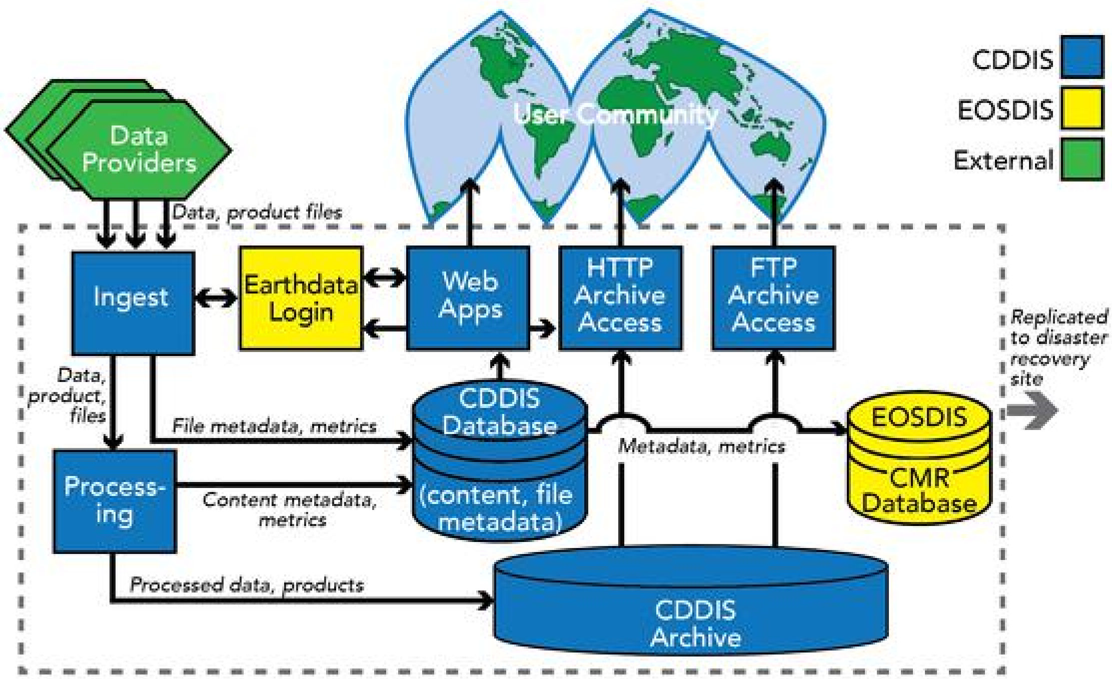

Figure 1: System architecture overview diagram for the CDDIS facility installation within the EOSDIS infrastructure.

all outgoing and incoming files along with dedicated 10G network connections between its primary operations and its backup operations. The use of the virtual machine technology provides multiple instance services for a load balancing configuration and allows for VM instances to be increased or decreased due to demand. Furthermore, the VM technology allows for system maintenance (patching, upgrades, etc.) to proceed without any downtime or interruption to user access. The large, unified storage system will easily accommodate future growth of the archive and facilitate near real-time replication between its production and disaster recovery sites. The entire archive is also mirrored to traditional storage arrays for additional complete copies of the archive. This system architecture has allowed the CDDIS to achieve an uptime figure of over 99.9 in 2017; some outages were outside CDDIS control, due to issues with EOSDIS facilities.

As shown in Figure 1, the providers of files for the CDDIS archive push their files (data, derived products, etc.) to the ingest server, utilizing the Earthdata Login system for access. Incoming files are then handled by the processing system which performs file/content validation and metrics extraction. Metadata and metrics (ingest/archive and distribution) information is pushed to the EOSDIS Common Metadata Repository (CMR) system. Content metadata, describing collections and granules are available for access by a broad user community through the CMR. Valid files are then moved to the CDDIS archive for public access through the CDDIS ftp and web servers.

3 Archive Contents

As a global data center for the IGS, the CDDIS is responsible for archiving and providing access to GNSS data from the global IGS network as well as the products derived from the analyses of these data in support of both operational and working group/pilot project activities. The CDDIS archive is approximately 21.5 Tbytes in size (over 220 million files) of which over 95% is devoted to GNSS data (19.5 Tbytes) and GNSS products (1.3 Tbytes). All these GNSS data and products are accessible through subdirectories of ftp://cddis.nasa.gov/gnss .

3.1 GNSS Data

3.1.1 Main Data Archive

The user community has access to GNSS data available through the on-line global data center archives of the IGS. Over 30 operational and regional IGS data centers and station operators make data (observation, navigation, and meteorological) available in RINEX format to the CDDIS from receivers on a daily, hourly, and sub-hourly basis. The CDDIS also accesses the archives of other IGS global data centers (GDCs), Scripps Institution of Oceanography (SIO) in California, the Institut Géographique National (IGN) in France,

Table 1: GNSS Data Type Summary.

Data Type	Sample Rate	Data Format	Available
Daily GNSS	30 sec.	RINEX V2	Since 1992
Daily GNSS	30 sec.	RINEX V3	Since 2016
Hourly GNSS	30 sec.	RINEX V2	Since 2005
Hourly GNSS	30 sec.	RINEX V3	Since 2016
High-rate GNSS	1 sec.	RINEX V2	Since 2001
High-rate GNSS	1 sec.	RINEX V3	Since 2016
Satellite GPS	10 sec.	RINEX V2	2002-2012

and the Korea Astronomy and Space Science Institute (KASI) to retrieve (or receive) data holdings not routinely transmitted to the CDDIS by an operational or regional data center. Table 1 summarizes the types of IGS GNSS data sets available in the CDDIS in the operational, non-campaign directories of the GNSS archive.

The main GNSS data archive (ftp://cddis.nasa.gov/gnss/data) at the CDDIS now contain GPS and GPS+GLONASS data in RINEX V2 format and multi-GNSS data in RINEX V3 format. Since January 2016, RINEX V3 data, using the V3 filename specification, have been made available here along with the RINEX V2 data. The availability of RINEX V3 data into the operational, main archives at the IGS GDCs (and detailed in the "RINEX V3 Transition Plan") addressed a key recommendation from the IGS 2014 Workshop: "one network one archive" and provided for the better integration of multi-GNSS data into the entire IGS infrastructure. Starting in 2015, stations began submitting RINEX V3 data using the format's "long" filename specification. The transition plan specified that RINEX V3 data from IGS network sites using the V3 filename structure should be archived in the same directory structure as the operational RINEX V2 data. Therefore, starting on January 01, 2016, all daily, hourly, and high-rate data submitted to the CDDIS in RINEX V3 format and using the long, V3 filename specification have been archived in the same directories as the RINEX V2 data (which use the 8.3.Z filename for daily and hourly files and the 10.3.Z filename format for high-rate files). In addition, these RINEX V3 files are compressed in gzip (.gz) format; files in RINEX V2 format continue to use UNIX compression (.Z). Furthermore, the data in RINEX V3 format include all available multi-GNSS signals (e.g., Galileo, QZSS, SBAS, BeiDou, and IRNSS) in addition to GPS and GLONASS. Figure 2 shows the network of IGS sites providing daily data in RINEX V2 and/or V3 formats.

The CDDIS archives three major types/formats of GNSS data, daily, hourly, and high-rate sub-hourly, all in RINEX format, as described in Table 1; the network distribution of submitted files is shown in Figure 3. All incoming files for the CDDIS archive are now checked for conformance to basic rules, such as valid file type, non-empty file, uses correct compression, consistency between filename and contents, uses correct file naming

Table 2: GNSS Data Archive Summary for 2017.

Data type	Number of sites V2	V3	V2&V3	Unique	Vol.	#file	Directory
Daily	349	37	215	601	700 GB	1.126 M	/gnss/data/daily
Hourly	205	9	152	366	235 GB	9.565 M	/gnss/data/hourly
High-rate	219	21	55	295	2,100 GB	13.530 M	/gnss/data/highrate

conventions, and other logic checks. After incoming files pass these initial checks, content metadata are extracted and the files undergo further processing based on data type and format.

Daily RINEX V2 data are quality-checked, summarized (using UNAVCO's teqc software), and archived to public disk areas in subdirectories by year, day, and file type; the summary and inventory information are also loaded into an on-line database. However, this data quality information, generated for data holdings in RINEX V2 format, is not available through the software used by CDDIS to summarize data in RINEX V3 format. CDDIS continues to investigate and evaluate software capable of providing data summary/QC information for RINEX V3 data. The CDDIS strongly recommends guidance from the IGS on identifying candidates for RINEX V3 QC software that can be used by data centers and users. Over 263K daily station days from 601 distinct GNSS receivers were archived at the CDDIS during 2017; of these sites, 215 sites supplied both RINEX V2 and V3 data (see Table 2). A complete list of daily, hourly, and high-rate sites archived in the CDDIS can be found in the yearly summary reports at URL `ftp://cddis.nasa.gov/reports/gnss/` .

Within minutes of receipt (typically less than 30 seconds), the hourly GNSS files are archived to subdirectories by year, day, and hour. Although these data are retained on-line, the daily files delivered at the end of the UTC day contain all data from these hourly files and thus can be used in lieu of the individual hourly files. As seen in Table 2, a total of 366 unique hourly sites (over 9.5 million files) were archived during 2017; 152 hourly sites provided data in both RINEX V2 and V3 formats.

High-rate (one-second sampling rate) GNSS data are made available in files containing fifteen minutes of data and in subdirectories by year, day, file type, and hour. Many of these data files are created from real-time streams. As shown in Table 2, data from 295 unique high-rate sites (over 13 million files) were archived in the CDDIS in 2017; 55 high-rate sites provided data in both RINEX V2 and V3 formats.

The CDDIS generates global RINEX V2 broadcast ephemeris files (for both GPS and GLONASS) on a daily and hourly basis. The hourly concatenated broadcast ephemeris files are derived from the site-specific ephemeris data files for each hour and are appended to a single file that contains the orbit information for all GPS and GLONASS satellites for the day up through that hour. The merged ephemeris data files, named `hourDDD0.YYn.Z`, are then copied to the day's subdirectory within the hourly data file system. Within 1-

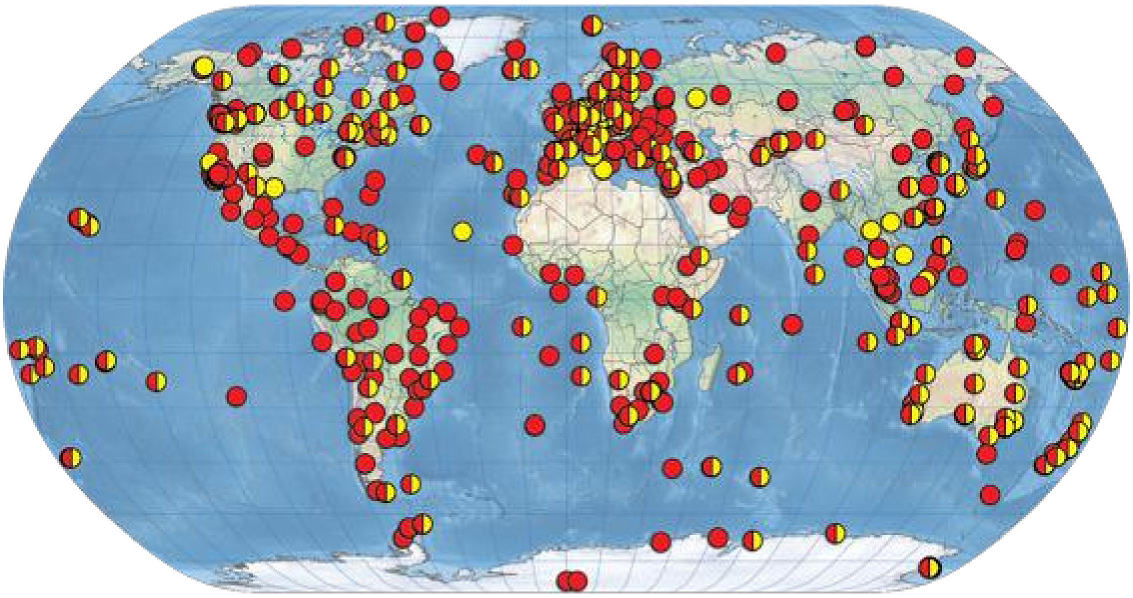

Figure 2: The main, operational archive at CDDIS now includes data in RINEX V2 format using the 8.3.Z filename specification (red) and RINEX V3 format using the V3 filename specification (yellow); sites providing both RINEX V2 and V3 formatted data are shown with the red+yellow icon.

2 hours after the end of the UTC day, after sufficient station-specific navigation files have been submitted, this concatenation procedure is repeated to create the daily broadcast ephemeris files (both GPS and GLONASS), using daily site-specific navigation files as input. These daily broadcast files, named `brdcDDD0.YYn.Z` and `brdcDDD0.YYg.Z`, are then copied to the corresponding year/day nav file subdirectory as well as the yearly brdc subdirectory (`/gnss/data/daily/YYYY/brdc`).

The CDDIS also generates daily RINEX V3 concatenated broadcast ephemeris files. The files are archived in the yearly brdc subdirectory (`ftp://cddis.nasa.gov/gnss/data/daily/YYYY/brdc`) with a filename of the form `BRDC00IGS_R_yyyydddhhmm_01D_MN.rnx.gz`. The procedure for generating these files is similar to the V2 procedure in that site-specific, mixed V3 ephemeris data files are merged into to a single file that contains the orbit information for all GNSS satellites for the day. The chair of the IGS Infrastructure Committee provided software that CDDIS staff uses to create these files.

Users can thus download this single, daily (or hourly) file to obtain the unique navigation messages rather than downloading multiple broadcast ephemeris files from the individual stations.

The CDDIS generates and updates "status" files, (`/gnss/data/daily/YYYY/DDD/YYDDD.status` for RINEX V2 data and `YYDDD.V3status` for RINEX V3 data) that summarize the holdings of daily GNSS data. These status files of CDDIS GNSS data holdings reflect

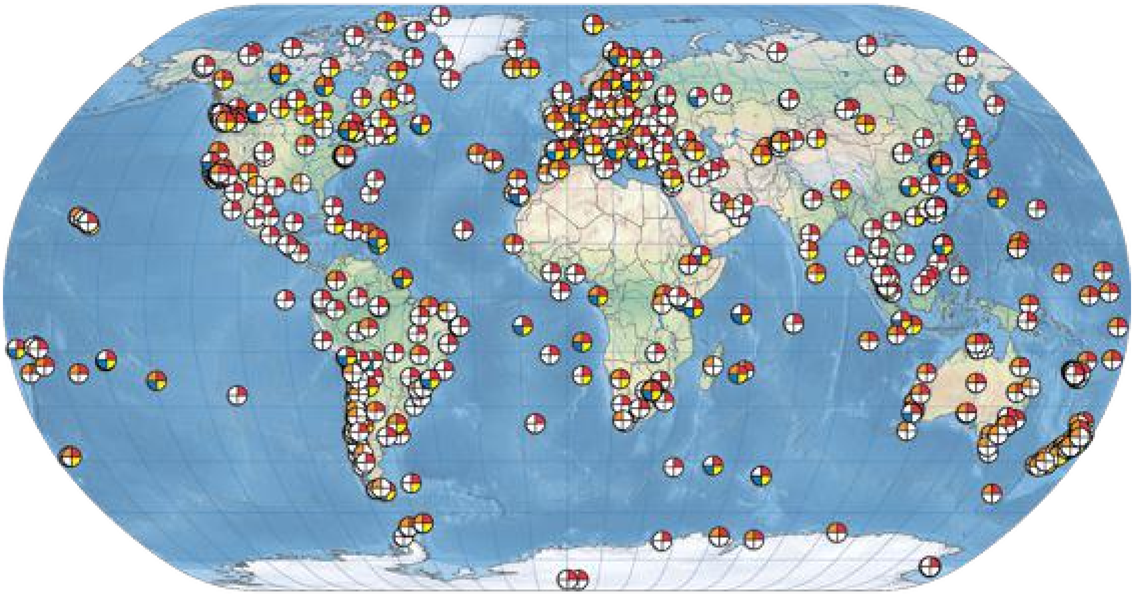

Figure 3: CDDIS GNSS archive includes data in daily (red), hourly (yellow), sub-hourly (blue), and/or real-time (orange) increments. Hourly, sub-hourly, and real-time data allow analysts to generate products for applications needing more frequent updates.

timeliness of the data delivered as well as statistics on number of data points, cycle slips, and multipath (for RINEX V2 data). The user community can thus view a snapshot of data availability and quality by checking the contents of such a summary file.

3.1.2 RINEX V3 (MGEX) Campaign Archive

During 2017, the CDDIS continued the archiving of data in RINEX V3 format from multi-GNSS receivers participating in the Multi-GNSS Experiment (MGEX) as well as products derived from the analysis of these data. Any data in RINEX V3 format but using the 8.3.Z filename specification, continue to be archived in a campaign directory structure at CDDIS (`/gnss/campaign/mgex/data`). In 2017, data from only one site (TWTF) were archived in this manner. All other sites providing RINEX V3 data utilize the RINEX V3 naming convention and are archived in the operational GNSS directories.

The CDDIS continues to archive a merged, multi-GNSS broadcast ephemeris file containing GPS, GLONASS, Galileo, BeiDou, QZSS, and SBAS ephemerides. This file, generate by colleagues at the Technical University in Munich (TUM) and Deutsches Zentrum für Luft- und Raumfahrt (DLR), is similar to the daily and hourly concatenated broadcast message files in RINEX V2 format provided by the CDDIS for the operational GPS+GLONASS data sets; it contains all the unique broadcast navigation messages for the day. The file, named `brdmDDD0.YYp.Z`, is stored in daily subdirectories within the

Table 3: GNSS Product Summary for 2017.

Product Type	Number of ACs/AACs	Volume	Directory
Orbits, clocks, ERP, positions	14+Combinations	3.6 GB/week	`/gnss/products/WWWW` (GPS, GPS+GLONASS) `/glonass/products/WWWW` (GLONASS only)
Troposphere	Combination	3 MB/day, 1.1 GB/year	`/gnss/products/troposphere/YYYY`
Ionosphere	7+Combination	5.5 MB/day, 2.0 GB/year	`/gnss/products/ionex/YYYY`
Real–time	Combination	28 MB/week	`/gnss/products/rtpp/YYYY`
MGEX	6	175 MB/week	`/gnss/products/mgex/YYYY`

Note: WWWW=4-digit GPS week number; YYYY=4-digit year

MGEX campaign archive at CDDIS (`/gnss/data/campaign/mgex/daily/rinex3/YYYY/DDD/YYp`) and in a yearly top level subdirectory (`/gnss/data/campaign/mgex/daily/rinex3/YYYY/brdm`).

Colleagues at TUM and DLR are also providing GPS and QZSS CNAV (civilian navigation) data on an operational basis within MGEX. These messages are collected from a sub-network of MGEX stations and are provided in a merged daily file in a format similar to RINEX. These files are named brdxDDD0.YYx.Z and stored in a daily subdirectory within the MGEX archive at CDDIS (`/gnss/data/campaign/mgex/daily/rinex3/YYYY/cnav`).

3.2 IGS Products

The CDDIS routinely archives IGS operational products (daily, rapid, and ultra-rapid orbits and clocks, ERP, and station positions) as well as products generated by IGS working groups and pilot projects (ionosphere, troposphere, real-time, MGEX). Table 3 below summarizes the GNSS products available through the CDDIS. The CDDIS currently provides on-line access through anonymous ftp to all IGS products generated since the start of the IGS Test Campaign in June 1992 in the file system `/gnss/products`; products from GPS+GLONASS products are available through this filesystem. Products derived from GLONASS data only continue to be archived at the CDDIS in a directory structure within the file system `/glonass/products`.

The CDDIS also continues to archive combined troposphere estimates in directories by year and day of year. Global ionosphere maps of total electron content (TEC) from the

IONEX AACs are also archived in subdirectories by year and day of year. Real-time clock comparison products have been archived at the CDDIS in support of the IGS Real-Time Pilot Project, and current IGS Real-Time Service, since 2009.

Six AACs (CODE, GFZ, GRGS, JAXA, TUM, and Wuhan) generated weekly products (orbits, ERP, clocks, and others) in support of MGEX; CODE and JAXA utilize the "long" filename convention for their products. These files are archived at the CDDIS in the MGEX campaign subdirectory by GPS week (`/gnss/products/mgex/WWWW`).

Colleagues at DLR and the Chinese Academy of Sciences (CAS) provide a differential code bias (DCB) products for the MGEX campaign. This product is derived from GPS, GLONASS, Galileo, and BeiDou ionosphere-corrected pseudorange differences and is available in the bias SINEX format. DLR has provided two files per year, daily satellite and daily satellite and station biases since 2013 in CDDIS directory `/gnss/products/mgex/dcb`; CAS provides daily files. Additional details on the DCB product are available in IGSMail message 6868 sent in February 2015 and message 7173 sent in October 2015. Both products use the new RINEX V3 file naming convention.

3.3 Real-Time Activities

In 2013, the CDDIS staff configured a server and began testing a caster to provide a real-time streaming capability at GSFC and support the IGS Real-Time Service (IGS RTS). The CDDIS successfully tested obtaining product streams from the BKG and IGS casters and providing access to these streams to authorized users; additional streams from Natural Resources Canada (NRCan) and Geoscience Australia (GA) were later added to the caster. Work was completed in spring 2015 and the CDDIS caster became fully operational. By the end of 2017, the CDDIS caster broadcasts nearly 40 product and over 330 data streams in real-time. The caster runs the NTRIP (Network Transport of RTCM via internet Protocol) format. Figure 4 shows the distribution of stations providing real-time streams to the CDDIS caster.

As stated previously, the CDDIS is one of NASA's EOSDIS DAACs and through EOSDIS, has access to a world-class user registration process, the EOSDIS Earthdata Login (EDL, formerly User Registration System, URS), with over 367K users in its system. Since the NTRIP-native registration/access software was not compatible with NASA policies, the CDDIS developed software to interface the caster and the EDL within a generic Lightweight Directory Access Protocol (LDAP) framework. The module was specifically developed to easily interface with multiple user verification systems and was given back to the NTRIP community for possible inclusion in future releases. New users complete a registration form available on the CDDIS website; once completed, the data are passed to the EDL, which generates an email to the user with a validation link. The user accesses the link and the EDL validates the form's data; this process is accomplished within a minute or less. The user's validated access request is submitted to CDDIS staff for access

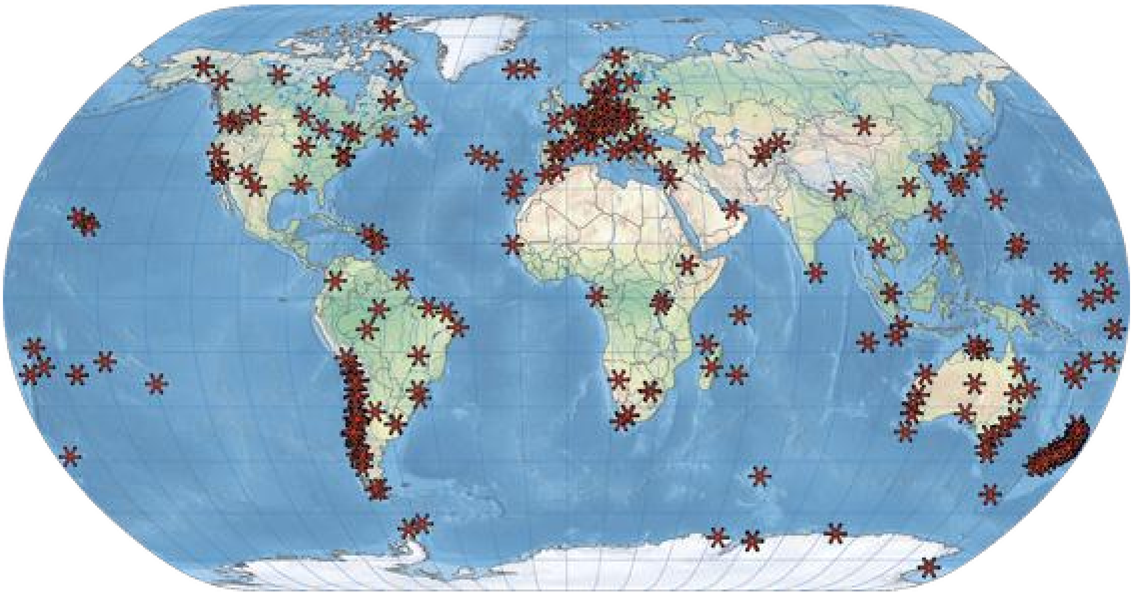

Figure 4: CDDIS is operationally supporting the dissemination of data from over 330 real-time GNSS sites as well as near real-time products derived from these data.

authorization to the CDDIS caster. This second step is not yet automated and can take several hours to configure depending on the time of day. In addition, users registering in this system have access to the entire suite of EOSDIS products across all 12 EOSDIS DAACs.

Initially, the CDDIS caster provided access to data and product streams from several regional real-time casters. Data streams have also been provided through JPL for receivers in NASA's Global GPS Network. In 2016, an additional set of stations from JPL's Global Differential GPS (GDGPS) network were added to the CDDIS caster. This network of globally distributed, geodetic quality, dual frequency receivers, provides additional 1 Hz data streams to those current available from the IGS RTS. The CDDIS caster was augmented with new real-time streams as they became available from IGS network sites. Several more GDGPS streams were added to the CDDIS caster in 2017.

The CDDIS is participating in tests with the Real-time Earthquake Analysis for Disaster Mitigation (READI) project by streaming GNSS data from a network in Chile. The CDDIS caster also makes streams available from other regional casters (e.g., in Australia and New Zealand)

The CDDIS caster serves as the third primary caster for the IGS RTS, thus providing a more robust topology with redundancy and increased reliability for the service. User registration, however, for all three casters is unique; therefore, current users of the casters located at the IGS/UCAR and BKG are required to register through the CDDIS registration process in order to use the CDDIS caster. By the end of 2017, over 180 users from 32 countries have registered to use the CDDIS caster. More information about the CDDIS caster is available at https://cddis-casterreg.gsfc.nasa.gov/index.html.

The CDDIS has also developed software to capture real-time data streams into fifteen-minute high-rate files. This capability requires further testing and coordination with the IGS Central Bureau and Infrastructure Committee before it is put into operational use.

3.4 Supporting Information

Daily status files of GNSS data holdings, reflecting timeliness of the data delivered as well as statistics on number of data points, cycle slips, and multipath, continue to be generated by the CDDIS for RINEX V2 data; status files, with limited information, summarizing RINEX V3 data holdings are also available. By accessing these files, the user community can receive a quick look at a day's data availability and quality by viewing a single file. The daily status files are available through the web at URL ftp://cddis.nasa.gov/reports/gnss/status. The daily status files are also archived in the daily GNSS data directories.

Ancillary information to aid in the use of GNSS data and products are also accessible through the CDDIS. Daily, weekly, and yearly summaries of IGS tracking data (daily, hourly, and high-rate) archived at the CDDIS are generated on a routine basis. These summaries are accessible through the web at URL ftp://cddis.nasa.gov/reports/gnss. The CDDIS also maintains an archive of and indices to IGS Mail, Report, Station, and other IGS-related messages.

4 System Usage

Figure 5 summarizes the usage of the CDDIS for the retrieval of GNSS data and products in 2017. This figure illustrates the number and volume of GNSS files retrieved by the user community during the past year, categorized by type (daily, hourly, high-rate, products). Over 1.3 billion files (nearly 135 Tbytes) were transferred in 2017, with an average of over 100 million files per month. Figure 6 illustrates the profile of users accessing the CDDIS GNSS archive during 2017. The majority of CDDIS users were from hosts in Asia, North America, and Europe.

CDDIS assisted staff at the newest IGS Global Data Center located at ESA/ESAC by generating tar files of GNSS data and products to facilitate the population of their archive.

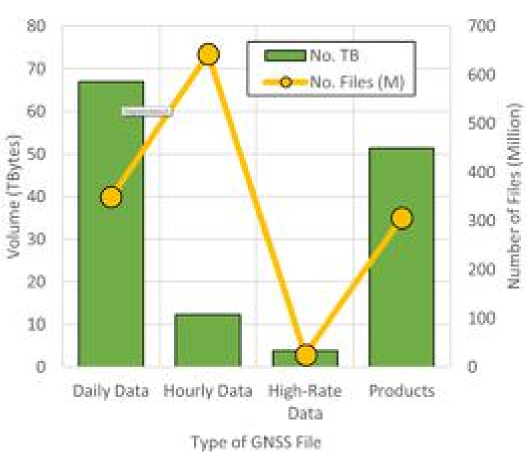

Figure 5: Number and volume of GNSS files transferred from the CDDIS in 2017.

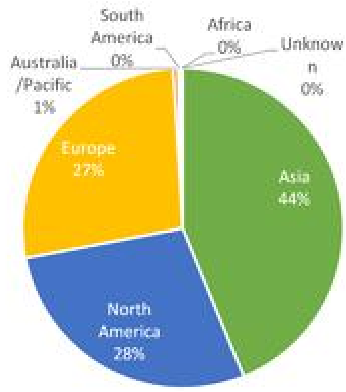

Figure 6: Geographic distribution of IGS users of the CDDIS in 2017.

5 Recent Developments

5.1 Archive Operations

The CDDIS has been operating for over 35 years. During that time procedures and processes have grown to meet both existing data archive needs and new requirements, which over time had become unwieldy and hard to support. Therefore, CDDIS conducted a complete review of the entire data ingest operations system in early 2016 to identify and correct process inefficiencies in and improve the QC of incoming files. Software development included the addition of more automation capabilities, better redundancy, easier supportability, and common code sharing. The staff developed and integrated new software to perform consistent processing on all data types. This new software performs routine checksums of and anti-virus scanning on all incoming files, extracts consistent file-level and content-level metadata, and consistently tracks file and content errors. The new operations software was implemented for GNSS data processing prior to the transition to the new hardware system and is now fully operational. In 2017, the software was implemented on other data types uploaded and archived at CDDIS (e.g., SLR and DORIS); testing on incoming VLBI data and product files will continue in 2018.

The software modifications implemented in the new CDDIS processing system allowed staff to check for errors in a more consistent fashion, regardless of data type or file provider. As these checks were automated, the CDDIS has been able to identify new errors, such as problems with file naming, compression, and content. The new software categorizes errors in incoming files as fatal or warning errors; errors are tracked in the CDDIS database allowing staff to more easily monitor data processing. Fatal errors include logic errors (e.g., data with a future date), an empty file, or an unknown file name/structure. Files with fatal errors are not moved to the archive; they are placed in a "quarantine" location for further examination by operations staff. Warning errors are generally auto-corrected/handled and the file is then archived; these errors include a significantly older file, invalid compression, etc.

This improvement in error detection has allowed the CDDIS operations staff to actively work with suppliers to correct a large majority of errors and thus provide users with access to an improved, more reliable CDDIS archive. Furthermore, the number of errors detected have been reduced significantly, mainly due to active communication and cooperation between CDDIS operations staff and file providers. Since GNSS data accounts for a large number of the incoming files to CDDIS, the staff has developed a guidelines document for data providers (https://cddis.nasa.gov/docs/2017/GNSSDataStandards_v2.pdf).

5.2 Data Upload System

The CDDIS now utilizes an https-based protocol method for delivery of files from suppliers of data and products. The authentication is performed through the EOSDIS Earthdata Login (EDL) system, the same system used for access to the CDDIS real-time caster. The file uploads can be performed through a webpage interface or a command line application that can perform an http "post" operation, which is more commonly used for scripting. This process allows data suppliers to authenticate through the EDL system and provide their files through https to CDDIS for ingest into the archive. Unfortunately, despite efforts of CDDIS staff to help, some data providers have been unable to update their procedures and software to use the new CDDIS upload system; this deficiency has affected CDDIS data holdings. Although the CDDIS staff continues to work with providers to utilize the upload system, new procedures were needed to retrieve files have been put in place to ensure the archive is as complete as possible. More information on the CDDIS file upload system, including an FAQ, is available at: https://cddis.nasa.gov/About/CDDIS_File_Upload_Documentation.html.

5.3 Archive Access

With EOSDIS requesting that EDL should also be used for archive access, the CDDIS has implemented a new method of providing a web-based archive access capability. Since its start, users have accessed the CDDIS archive through anonymous ftp. This protocol allows users to easily automate file downloads but often has problems from a system and user standpoint. Therefore, as many public archives and users continue to move away from using ftp, the CDDIS has implemented https access to its full archive. This https access will continue to use same structure as that provided through ftp and is as efficient as ftp transfer without the firewall/router issues of ftp. For example, since ftp is a two-port protocol, users can have connectivity problems (e.g., with firewall, DNS, etc.). However, http is a one-port protocol and thus has fewer issues with downloads. The CDDIS will eventually utilize the Earthdata Login system for access through https. Even though ftp access to the CDDIS archive will continue; users, however, are encouraged to explore the new https capabilities. As stated previously, users with Earthdata Login credentials have easy access to the broad number of products available through all 12 EOSDIS DAACs. In addition, Earthdata Login will allow CDDIS to know our users better which will then allow staff to improve CDDIS capabilities.

The CDDIS continues to maintain two applications for querying site information or archive contents. The Site Log Viewer (https://cddis.nasa.gov/Data_and_Derived_Products/SiteLogViewer/index.html) is an application for the enhanced display and comparison of the contents IAG service site log (currently IGS, ILRS, and IDS). A second application, the CDDIS Archive Explorer (https://cddis.nasa.gov/Data_and_Derived_Products/CddisArchiveExplorer.html) allows users to discover what data are available through the CDDIS. The application provides users the ability to specify search criteria based on temporal, spatial, target, site designation, and/or observation parameter in order to identify data and products of interest for download.

5.4 Metadata Developments

The CDDIS continues to make modifications to the metadata extracted from incoming data and product files pushed to its archive and implemented these changes in the new operations software system. These enhancements have facilitated cross discipline data discovery by providing information about CDDIS archive holdings to other data portals such as Earth Observing System search client and future integration into the GGOS portal. The staff continues work on a metadata evolution effort, re-designing the metadata extracted from incoming data and adding information that will better support EOSDIS applications such as its search client and the metrics collection effort. The CDDIS is also participating in GGOS metadata efforts within the Bureau of Networks and Observations.

The CDDIS continues to implement Digital Object Identifiers (DOIs) to select IGS data sets (GNSS data and products). DOIs can provide easier access to CDDIS data holdings and allow researchers to cite these data holdings in publications. Landing pages are available for each of the DOIs created for CDDIS data products and linked to description pages on the CDDIS website; an example of a typical DOI description (or landing) page, for daily Hatanaka-compressed GNSS data files, can be viewed at: https:/cddis.nasa.gov/Data_and_Derived_Products/GNSS/daily_gnss_d.html . DOIs will be assigned to additional GNSS data and product sets in the near future.

6 Publications

The CDDIS staff attended several conferences during 2017 and presented, or contributed to, papers on their activities within the IGS, including:

Michael, P. and C. Noll. "Supporting GGOS Through NASA's Archive of Space Geodesy Data and Products" (poster), presented at European Geosciences Union General Assembly 2017, Vienna, Austria, April 24-28, 2017, Abstract No. EGU2017-10698.

Pearlman, M., C. Noll, C. Ma, E. Pavlis, R. Neilan, J. Saunier, T. Schoene, R. Barzaghi, D. Thaller, S. Bergstrand, and J. Mueller. "The GGOS Bureau of Networks & Observations: An Update on the Space Geodesy Network & the New Implementation Plan for 2017-2018" (poster), presented at European Geosciences Union General Assembly 2017, Vienna, Austria, April 24-28, 2017, Abstract No. EGU2017-10698.

Noll, C. and P. Michael. "An Update on the CDDIS IGS Global Data Center" (poster). Presented at IGS Workshop 2017, Paris, France, July 03-07, 2017.

Blevins, S., P. Michael, and C. Noll. "Real-time data and product performance metrics at NASA GSFC CDDIS" (poster). Presented at IGS Workshop 2017, Paris, France, July 03-07, 2017.

Woo, J., R. Limbacher, C. Noll, and P. Michael. "GNSS Quality Control Improvements and Provider Performance Tracking at the Crustal Dynamics Data Information System (CDDIS)" (poster). Presented at IGS Workshop 2017, Paris, France, July 03-07, 2017.

Pearlman, M. and C. Noll. "The GGOS Bureau of Networks and Observations" (poster). Presented at the IAG and IASPEI Joint Scientific Assembly, Kobe, Japan, July 30 - August 04, 2017.

Noll, C., P. Michael, J. Woo, and R. Limbacher. "NASA CDDIS: Next Generation System" (poster). Presented at the Fall American Geophysical Union meeting, New Orleans, LA, USA, December 11-15, 2017

Blevins, S., L. Hayes, Y. Collado-Vega, P. Michael, and C. Noll. "Survey of localized solar flare signatures in the ionosphere with GNSS, VLF, and GOES observations" (poster). Presented at the Fall American Geophysical Union meeting, New Orleans, LA, USA, December 11-15, 2017

Electronic versions of these and other publications can be accessed through the CDDIS on-line documentation page on the web at URL https://cddis.nasa.gov/Publications/Presentations.html.

7 Future Plans

7.1 Archive Access

The https access to the CDDIS archive will become fully operational in 2018. CDDIS staff will work with users to transition their processing to use of https instead of anonymous ftp.

7.2 RINEX V3 Data

The CDDIS will continue to coordinate with the Infrastructure Committee, the Data Center Working Group, and other IGS data centers to implement steps outlined in the RINEX V3 transition plan to complete the incorporation of RINEX V3 data into the operational GNSS data directory structure. The CDDIS began this process with multi-GNSS, RINEX V3 data from January 2016 onwards; the CDDIS will continue these efforts by integrating RINEX V3 multi-GNSS data from years prior to 2016 into the IGS operational archives. MGEX campaign directories will continue to be maintained during this transition to the operational directory archive. Furthermore, the CDDIS staff will continue to test software to copy RINEX V3 data (using the older filename format) into files with RINEX V3 filenames as well as QC RINEX V3 data and files and incorporate the software into operational procedures.

7.3 Real-Time Activities

The CDDIS will continue to add real-time data and product streams to its operational caster in support of the IGS Real-Time Service. Future activities in the real-time area include capturing the streams for generation of 15-minute high-rate files for archive. This capability requires further testing and coordination with the IC. The staff is also developing software to provide metrics on usage of the CDDIS caster. The staff will also investigate automating the process of adding users to the CDDIS caster configuration files.

8 Contact Information

To obtain more information about the CDDIS IGS archive of data and products, contact:

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9 Acknowledgments

Funding for the CDDIS, and its support of the IAG, IGS and other services, is provided by NASA through the Earth Science Data and Information System (ESDIS) project, which manages the EOSDIS science systems and DAACs.

The author would like to acknowledge the CDDIS deputy manager, Patrick Michael, the CDDIS contractor staff, Sandra Blevins, Maurice Dube, Rebecca Limbacher, and Nathan Pollack (Science Systems and Applications, Inc./SSAI), Lori Tyahla (Stinger Ghaffarian Technologies/SGT), Justine Woo (Sigma Space Inc.), and Jennifer Ash and James Roark (ADNET Systems). The success of the CDDIS and its recognition in the many international programs supported by the system can be directly attributed to the continued dedicated, consistent, professional, and timely support of its staff.

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Noll, C., Y. Bock, H. Habrich, and A. Moore Development of data infrastructure to support scientific analysis for the International GNSS Service Journal of Geodesy, Feb 2009, pages 309-325, DOI 10.1007/s00190-008-0245-6.

IGS RINEX 3 Transition Plan v3.0 IGS website, http://kb.igs.org/hc/en-us/article_attachments/202584007/Rinex_3_transition_plan_v3.0.pdf.

The Receiver Independent Exchange Format. Version 3.03 IGS website, ftp://igs.org/pub/data/format/rinex303.pdf.

BKG Regional Data Center Technical Report 2017

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1 Introduction

Since 25 years, BKG is contributing to the IGS data center infrastructure operating a regional GNSS data center (GDC). BKG's GDC is also serving as a data center for the regional infrastructure of EUREF. As a second pillar, since 2004, BKG is operating various entities for the global, regional and national real-time GNSS infrastructure. The development of the basic real-time components has been done independently from the existing file-based data center. The techniques behind, the user access etc. were completely different from the existing file-based structure. Moreover, operation of a real-time GNSS service demands a much higher level of monitoring than it is necessary in the post-processing world, where for example RINEX files can be reprocessed the next day in case of an error. However, there are several common features and interfaces like site log files, skeleton files, and high-rate files. Therefore, the goal is the public outreach as one GDC and to simplify user access to both infrastructures, e.g. via one web interface.

2 GDC Archive

2.1 Infrastructure

Currently BKG's GDC is running on a server integrated in a virtual machine environment placed at BKG's premises. It consist of a file server, a database server and a server dedicated to data processing and web access. All relevant parts of BKG's GDC are backed-up on a daily basis and stored on tape for at least a month before being over written. The virtualization has proved to be reliable, and downtimes due to system maintenance haven't been necessary. A disaster recovery system for the GDC is not installed and not scheduled currently.

2.2 Access

The access to the data center is possible via FTP, HTTPS and web interface. The web interface allows the following activities:

- Full “Station List” with many filtering options and links to meta data
- File browser
- Search forms for RINEX files as well as for any file
- Availability of daily and hourly RINEX files
- Interactive map allowing condensed information about each station

A processing monitor informs about the average time needed to process a single RINEX file and the amount of RINEX files stored daily or hourly. Changes in the processing software or system hardware are indicated as well.

The FTP commands allow easy access for anonymous download of many files and for implementation in download scripts.

2.3 GNSS Data & Products

The BKG GDC contains all the regular GNSS data, as there are navigational data, meteorological data, observational data, both RINEX v2 and RINEX v3, daily, hourly and high-rate (i.e. 1 Hz) data.

The directory structure applied by BKG is project-driven, i.e. within the “Data Access” a user will see IGS, EUREF, GREF, MGEX directories plus some other or historic projects. The main sub-directories for the projects are

- `BRDC` for the navigational data,
- `highrate` for the sub-hourly 1 Hz data,
- `nrt` for 30 seconds hourly data,
- `obs` for the daily data.

Since at the beginning of storing Rx3 files the standard short file names were identical to those containing Rx2, BKG decided to introduce parallel sub-directories with the extension `_v3`. It is expected that these directories will be obsolete in the near future.

The introduction of long file names has been continued. For example, only five stations were still delivering RX3 daily observational files with short file names in December 2017 in the IGS sub-directory `obs_v3`. So the specific sub-directories might become obsolete during 2018.

For completeness, BKG is also providing some IGS products by mirroring from, e.g. CDDIS. Each project has some additional sub-directories: products, reports, and stations.

Figure 1 gives a complete overview about the existing directory structure and the contents of each directory of BKG's GDC. You can also find the detailed FTP structure of all projects on https://igs.bkg.bund.de/dataandproducts/ftpstructure.

GREF	BRDC	YYYY	DDD		Spliced RINEX Navigation Files
	BRDC_v3	YYYY	DDD		
	highrate	YYYY	DDD	HH	RINEX Navigation and Observation Data (1Hz)
	highrate_v3	YYYY	DDD	HH	
	nrt	DDD	HH		RINEX Navigation and Observation Data (30 s)
	nrt_v3	DDD	HH		
	obs	YYYY	DDD		
	obs_v3	YYYY	DDD		
	products	wwww			Geocentric Station Coordinates, Atmospheric Parameters
	station				Metadata on Stations
	reports				Information on File Availability
EUREF	BRDC	YYYY	DDD		Spliced RINEX Navigation Files
	BRDC_v3	YYYY	DDD		
	highrate	YYYY	DDD	HH	RINEX Navigation and Observation Data (1Hz)
	highrate_v3	YYYY	DDD	HH	
	nrt	DDD	HH		RINEX Navigation and Observation Data (30 s)
	nrt_v3	DDD	HH		
	obs	YYYY	DDD		
	obs_v3	YYYY	DDD		
	products	wwww			Geocentric Station Coordinates, Atmospheric Parameters
	station				Metadata on Stations
	reports				Information on File Availability
EPNrepro2	products	wwww			Geocentric Station Coordinates, Atmospheric Parameters
IGS	BRDC	YYYY	DDD		Spliced RINEX Navigation Files
	BRDC_v3	YYYY	DDD		
	highrate	YYYY	DDD	HH	RINEX Navigation and Observation Data (1Hz)
	highrate_v3	YYYY	DDD	HH	
	nrt	DDD	HH		RINEX Navigation and Observation Data (30 s)
	nrt_v3	DDD	HH		
	obs	YYYY	DDD		
	obs_v3	YYYY	DDD		
	products	EOP_ERP			Earth Rotation Parameters
		glo_orbits	wwww		Orbit and Clock Corrections, Atmospheric Parameters
		orbits	wwww		
		mgex	wwww		
	station				Metadata on Stations
	reports				Information on File Availability
MGEX	BRDC	YYYY	DDD		Spliced RINEX Navigation Files
	BRDC_v3	YYYY	DDD		
	highrate	YYYY	DDD	HH	RINEX Navigation and Observation Data (1Hz)
	highrate_v3	YYYY	DDD	HH	
	nrt	DDD	HH		RINEX Navigation and Observation Data (30 s)
	nrt_v3	DDD	HH		
	obs	YYYY	DDD		
	obs_v3	YYYY	DDD		
	station				Metadata on Stations
	reports				Information on File Availability
NTRIP	BRDC	YYYY	DDD		Spliced RINEX Navigation Files
	BRDC_v3	YYYY	DDD		

Figure 1: Directory structure and contents of the BKG GNSS Data Centre (GDC).

2.4 Monitoring

Routinely, data-checks are performed for all incoming files. The files are processed through several steps, see Goltz et al. (2017) for details. An "Error Log" page on the web interface gives valuable information especially to the data providers how often and for what reasons a file was excluded from archiving.

On the "Station List" page (https://igs.bkg.bund.de/dataandproducts/stationqclist) a user or a data provider can see the completeness of the most recent data. You can also see some simple positioning time series for each station.

A new service under development is the "REST Web Service" (https://igs.bkg.bund.de/index/rest). A request for a specific file, a station or a complete GNSS network returns a compact information in either JSON or XML format.

2.5 System Usage

More than 13 million files are stored in the GDC with approx. 3 TByte of storage needed. We are facing with approx. 80,000 uploads and 66,0000 downloads per day. The increase in number of files with respect to 2016 was 45% for upload and 30% in download, resp. The full number of users may reach 8000 per hour, with approx. 85 different users. It should be mentioned that approx. 450 users per day are accessing the GDC via the http access.

3 Real-Time

3.1 Infrastructure

The development of the broadcaster technology and its usage for GNSS was mainly driven by BKG. It is originally based on the ICECAST technology and adapted for GNSS data (Weber et al. 2005). Since 2008, BKG is offering the so-called Professional Ntrip Caster which is used by various organizations and companies around the globe and which is updated and improved on a regular basis. BKG is maintaining various broadcasters for global, regional and national purposes. BKG's caster are not on own premises but hosted by an external service provider. The advantage of going this way clearly is the independency of local restrictions. Likewise for the file-based infrastructure – or even more important – is the aspect of redundancy. The redundancy concept for real-time streaming on the data center's side is realized in different ways. Firstly, the various casters are installed on different virtual machines at the service provider, so if one machine fails not all real-time streams are interrupted at the same time.

3.2 Access

The access to the broadcasters is possible with many commercial or individual tools. One software tool for easy access to the various IGS resources is the BKG Ntrip Client (BNC, Weber et al. (2016)). Since BNC has been developed always in parallel and close connection to the Professional broadcaster development, it is perfectly suited to the open IGS infrastructure.

3.3 GNSS Data & Products

As mentioned before, BKG is maintaining different casters (status end of 2017):

- On the mgex-ip caster (http://mgex.igs-ip.net) we are providing real-time date of approx. 90 stations. Almost all of the streams are received in raw data format. The streams are then converted by EURONET software into RTCM 3.2/3.3 MSM format.
- On the euref-ip caster (http://www.euref-ip.net) we are providing approx. 161 data streams in RTCM3.0/1/2 format. There is still a dozen streams available in the old RTCM 2.x format.
- On the igs-ip caster (http://www.igs-ip.net) we are providing approx. 178 data streams in RTCM3.0/1/2/3 format. There are still five streams available in the old RTCM 2.x format.

www.gref-ip.de	RTCM 3.1/3.2 Navigation and Observation Data with short mount point names (1 Hz)
	Proprietary Navigation and Observation Data with short mount point names (1 Hz)
	RTCM 3.3 Broadcast Ephemeris for BDS, GAL, GLO, GPS, QZS, SBAS (5 s)
	RTCM 3.3 Orbit & Clock corrections referred to national datum (10 s)
	Specifications on record types (CAS, NET, STR) included in source-table
www.euref-ip.net	RTCM 2.2/2.3/3.0/3.1/3.2/3.3 Navigation and Observation Data with short and long mount point names (1Hz)
	RTCM 3.0 Orbit & Clock Corrections, Code Biases referred to ETRS89 (10 s)
	Specifications on record types (CAS, NET, STR) included in source-table
www.igs-ip.net	RTCM 2.3/3.0/3.1/3.2/3.3 Navigation and Observation Data with short and long mount point names (1Hz)
	Specifications on record types (CAS, NET, STR) included in source-table
mgex.igs-ip.net	RTCM 3.2/3.3 Navigation and Observation Data with short mount point names (1Hz)
	Proprietary Navigation and Observation Data with short mount point names (1 Hz)
	RTCM 3.3 Broadcast Ephemeris for BDS, GAL, GLO, GPS, QZS, SBAS (1 Hz)
	Specifications on record types (CAS, NET, STR) included in source-table
products.igs-ip.net	RTCM 3.0/3.1 Orbit and Clock Corrections, Code Biases referred to APC for GLO, GPS (5 or 10 s)
	RTCM 3.0/3.1 Orbit and Clock Corrections, Code Biases referred to CoM for GLO, GPS (5 or 10 s)
	RTCM 3.0 Orbit and Clock Corrections, Code and Phase Biases referred to APC for GAL, GLO, GPS (5 s)
	RTCM 3.0 Orbit and Clock Corrections, Code and Phase Biases referred to CoM for GAL, GLO, GPS (5 s)
	RTCM 3.2/3.3 Broadcast Ephemeris for BDS, GAL, GLO, GPS, QZS, SBAS (1 Hz)
	RTCM 3.0 Orbit & Clock corrections referred to various regional datums (10 s)
	Specifications on record types (CAS, NET, STR) included in source-table

Figure 2: Names and contents of BKG Broadcasters.

- On the products-ip caster (http://products.igs-ip.net) we are providing approx. 55 data streams in RTCM3.0/1/2 format. These streams divide in clock and orbit correction streams from various organizations and in ephemeris data streams. There are various ephemeris streams available, mainly due to requests of specific user groups, e.g. constellation-specific data streams.

Figure 2 gives a complete overview about the BKG broadcasters and the contents of each broadcaster. The information on the meta-data (e.g. format, message types, sampling rates, receiver type) can be found in the source-table of each caster. BKG also offers a source-table checker (https://igs.bkg.bund.de/ntrip/chksourcetable) allowing a user to verify his own source-table against the (official) content described at http://software.rtcm-ntrip.org/ .

3.4 Monitoring

Besides the monitoring of the orbit and clock correction streams which is mainly done by the IGS Real-Time Coordinator during its combination process a qualitative analysis is carried out by using the various correction streams within the precise point positioning (PPP) in real-time (https://igs.bkg.bund.de/ntrip/ppp). On the one hand, it is done for the GREF mount-points using BKG's GPS+GLONASS correction stream CLK11. On the other hand, it is done using all individual corrections streams for GPS-only and GPS+GLONASS as well as the combined streams with the IGS station FFMJ. Moreover, global performance is monitored by using 24 different IGS real-time stations for each correction stream every day (https://igs.bkg.bund.de/ntrip/ppp#Scene15).

3.5 System Usage

While there is anonymous download for the file-based data, a registration is necessary for accessing real-time data (https://register.rtcm-ntrip.org/cgi-bin/registration.cgi). Since 2008, the demand for registration at BKG is unchanged on the level of approx. 400 requests per year (Figure 3). However, many of such registrations show up for a small amount of time only. Nevertheless, the number of so-called listeners, i.e. the requested data streams in parallel, reaches more than 2500 from approx. 50 different users during a typical day. The data volume sent to the users is roughly 10 times higher than the received data (Figure 4).

For the IGS and the EUREF caster we have a mean upload of 7 GByte per day for each caster and a download of 125 GByte and 50 GByte per day, resp. For the MGEX caster, however, we are confronted with a mean upload of 22 GByte per day and a download of 185 GByte per day. For the PRODUCTS caster, finally, we have a smaller upload of 1 GB per day and a download of 27 GB per day. This sums up to a traffic of more than 400 GByte per day for the four caster (Figure 4).

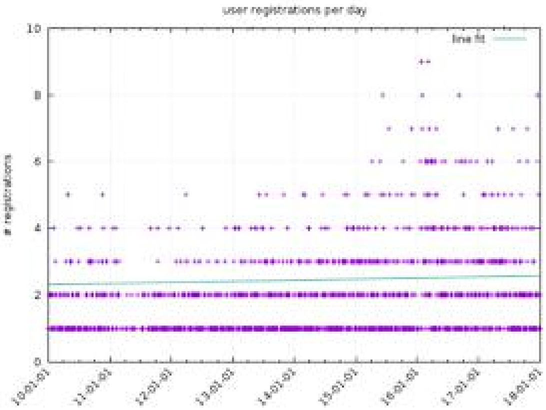

Figure 3: Number of registrations per day for BKG Broadcasters since 2010.

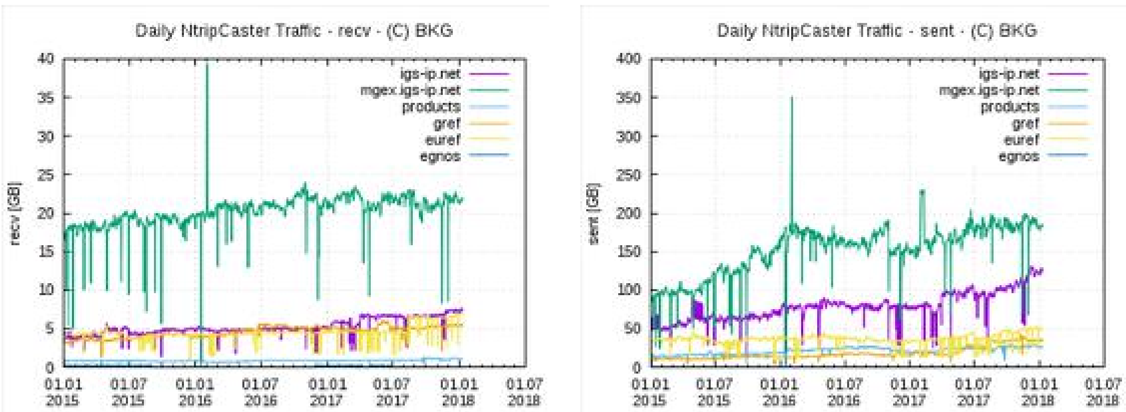

Figure 4: Daily received (i.e., upload to BKG, left) and sent (i.e., download from BKG) data volume at the BKG Broadcasters since 2015.

4 Future Plans

In 2018, the introduction of the long mount point names will be completed. A new interface to station meta data via GeodesyML is projected. Moreover, a fundamental IT consolidation process within the German federal government has been instructed, which started in 2016 and is expected to be finalised in 2018, extensively affecting almost all activities of BKG.

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Part IV

Working Groups, Pilot Projects

Antenna Working Group Technical Report 2017

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1 Introduction

The IGS Antenna Workingroup establishes a contact point to users of IGS products, providing guidance for antenna calibration issues and for a consistent use of IGS products. It maintains the IGS files related to receiver and antenna information, namely the IGS ANTEX file including satellite antenna and receiver type-mean calibrations.

Antenna phase center issues are related to topics such as reference frame, clock products, calibration, monumentation. The Antenna WG therefore closely cooperates with the respective working groups (Reference Frame WG, Clock Product WG, Bias and Calibration WG, Reanalysis WG), with antenna calibration groups, with the Analysis Center Coordinator and the Analysis Centers for analysis related issues, and with the Network Coordinator concerning maintenance of relevant files.

2 Chamber calibrated satellite patterns

2.1 Galileo and QZSS

In 2016, GSA (GSA 2017a, b) has disclosed the IOV satellite antenna calibrations followed by the FOC satellite antenna calibrations in October 2017. With their disclosure, the full GNSS constellation has been released. The antenna working group has decided during the splinter meeting at the IGS Workshop 2017 in Paris to include the IOV calibrations into the official IGS ANTEX file after an evaluation period of one month. In September 2017 a testing version of the IGS ANTEX files (IGS-Mail #7527) has been published on

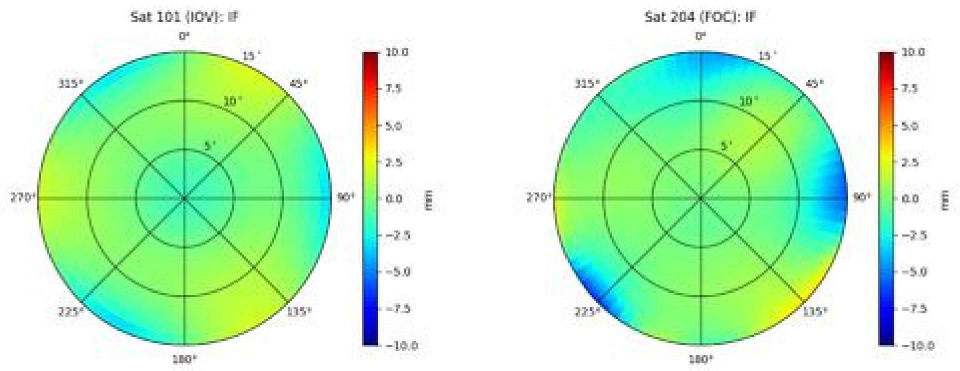

Figure 1: Phase variations for the ionosphere-free linear combination for IOV satellite E101 (left)and FOC satellite E204 (right).

the IGS ftp server and, after the testing trial period, it became the official IGS ANTEX release (igs14_ 1972.atx, IGS-Mail #7543).

The next steps in 2018 will be to introduce the remaining Galileo (FOC) and replace the estimated values (Steigenberger et al. 2016). In addition to the Galileo system, CAO also released their meta information about the QZS 1-4 satellites including the satellite antenna calibrations (CAO 2017). The pattern shall also be added to the official IGS ANTEX files. With these two additional replacements of the old IGS pattern by their actual chamber calibrations, a global (Galileo) and a regional (QZSS) GNSS will be represented by their chamber calibrations instead of using estimated values. Figure 1 shows the phase variations for satellite E101 (IOV)and E204 (FOC).

2.2 Impact for receiver antennas

With the release of the chamber calibrated satellite pattern, the missing frequencies for the ground sites, in particular for E5 and L5, becomes a limiting factor for a combined GNSS analysis. With the estimated pattern for Galileo (Steigenberger et al. 2016) the situation is less critical as the average difference between L1/L2 and E1/E5 ionosphere free linear combination (IF) offsets were absorbed by the satellite phase center offsets. With calibrated values this is no longer the case.

Within the EUREF network several individual chamber calibrations are available which contain, among others, also patterns for E5 and L5. These calibrations allow to determine the difference between IF PCOs derived from L1/L2 and E1/E5. The difference between them can be up to 1 cm and harms the coordinate estimation if they are no properly applied. The comparison of the up component is listed in Table 1. The situation of missing calibrations for Galileo can be relaxed by introducing additional parameters for the offset between the GPS and the Galileo antenna reference point. However, this leads

Table 1: Comparison of phase center offsets (upward component only) from chamber calibrations (published be the EUREF). The mean difference between using L1/L2 and E1/E5 is up to 1 cm.

STA	Antenna type	PCO (IF) L1 / L2 [mm]	E1 / E5 [mm]	Δ PCO [mm]
BRUX	JAVRINGANT_DM NONE	65.19	56.62	-8.56
POTS	JAV_RINGANT_G3T NONE	48.97	39.75	-9.22
OBE4	JAV_RINGANT_G3T NONE	49.18	39.28	-9.90
NYA2	JAV_RINGANT_G3T NONE	50.40	41.17	-9.23
BADH	LEIAR10 NONE	96.22	94.74	-1.49
WRLG	LEIAR25.R3 LEIT	151.72	148.89	-2.84
DOUR	LEIAR25.R3 NONE	146.59	143.55	-3.04
REYK	LEIAR25.R4 LEIT	149.68	145.31	-4.36
HOFN	LEIAR25.R4 LEIT	149.12	144.92	-4.20
NICO	LEIAR25.R4 LEIT	148.09	143.56	-4.54
EUSK	LEIAR25.R4 LEIT	149.52	145.20	-4.32
ISTA	LEIAR25.R4 LEIT	155.77	149.24	-6.53

to two sets of coordinates for one station. This problematic needs further investigation, especially once the chamber calibrated satellite pattern for full Galileo constellation is included in the IGS ANTEX file.

3 Updates and content of the antenna phase center model

Table 2 lists all updates of the `igs14_wwww.atx` in 2017. 10 new antenna/radom combinations have been added. Moreover, the IOV satellite pattern where replaced with their chamber calibrations.

4 Calibration status of the IGS network

Table 3 shows the percentage of IGS tracking stations with respect to certain calibration types. For this analysis, 508 IGS stations as contained in the file `logsum.txt` (available at `ftp://igs.org/pub/station/general/`) were considered. At that time, 99 different antenna/radome combinations were in use within the IGS network. The calibration status of these antenna types was assessed with respect to the phase center model `igs14_wwww.atx` that were released in December 2017.

The overall situation regarding the stations with state-of-the-art robot-based calibrations

Table 2: Updates of the phase center model `igs14_wwww.atx` in 2017 (`wwww`: GPS week of the release date; model updates restricted to additional receiver antenna types are only announced via the *IGS Equipment Files* mailing list)

Week	Date	IGSMAIL	Change		
1935			Added	`STHCR3-G3`	`STHC`
				`TWIVP6050_CONE`	`NONE`
1941			Added	`ARFAS1FS`	`ARFC`
				`SOKGCX3`	`NONE`
1943			Added	`STXS9I`	`NONE`
1949			Added	G038 (G04)	
			Decommission date: G049 (G04)		
1958			Added	G036 (G04)	
			Decommission date: G038 (G04)		
			Added	`SJTTL111`	`NONE`
1967			Added	R801 (R14)	
			Decommision date: R715 (R14), R801(R26)		
1972	24. Oct. 2017		Chamber calibrated PCO and PCV for Galileo IOV satellites: IOV-PFM,IOV-FM2,IOV-FM3,IOV-FM4		
			Added	`IGAIG8`	`NONE`
1973	2. Nov. 2017		Added	R852 (R14), 801 (R26)	
			Decommision date: R801(R14)		
			Added	`HXCCGX601A`	`HXCS`
				`SEPALTUS_NR3`	`NONE`
1977	1. Dec. 2017		Added	G049 (G04)	
			Decommision date: G036 (G04)		
			Added	`LEIGS18`	`NONE`

Table 3: Calibration status of 508 stations in the IGS network (`logsum.txt` vs. `igs14_wwww.atx`) compared to former years

Date		Absolute calibration (azimuthal corrections down to 0° elevation)	Converted field calibration (purely elevation-dependent PCVs above 10° elevation)	Uncalibrated radome (or unmodeled antenna subtype)
DEC 2009		61.4%	18.3%	20.2%
MAY 2012		74.6%	8.2%	17.2%
JAN 2013		76.8%	7.7%	15.5%
JAN 2014		78.7%	7.8%	13.5%
JAN 2015		80.1%	7.5%	12.4%
JAN 2016		83.0%	6.5%	10.5%
JAN 2017	igs08.atx:	84.9%	6.2%	8.9%
	igs14.atx:	90.7%	2.2%	7.1%
JAN 2018	**igs14.atx:**	**92.1%**	**2.2%**	**5.7%**

keeps improving by about 2% per year after the improvement of 6% with the change from the igs08.atx to the igs14.atx where additional robot-based calibrations have been added. Finally, new calibrations for certain antenna/radom combinations have been added to the igs14.atx.

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GSA Galileo IOV and FOC Satellite Antenna Calibrations, SINEX code GSAT_1934 URL https://www.gsc-europa.eu/sites/default/files/sites/all/files/ANTEX_GAL_FOC_IOV.atx (accessed 18/01/26)

GSA Galileo IOV and FOC satellite metadata URL: https://www.gsc-europa.eu/support-to-developers/galileo-iov-satellite-metadata (accessed 18/01/26)

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Bias and Calibration Working Group Technical Report 2017

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1 Introduction

The IGS Bias and Calibration Working Group (BCWG) coordinates research in the field of GNSS bias retrieval and monitoring. It defines rules for appropriate, consistent handling of biases which are crucial for a "model-mixed" GNSS receiver network and satellite constellation, respectively. At present, we consider: GPS C1W–C1C, C2W-C2C, and C1W–C2W differential code biases (DCB). Potential quarter-cycle biases between different GPS phase observables (specifically L2P and L2C) are another issue to be dealt with. In the face of GPS and GLONASS modernization programs and upcoming GNSS, like the European Galileo and the Chinese BeiDou, careful treatment of measurement biases in legacy and new signals becomes more and more crucial for combined analysis of multiple GNSS.

The IGS BCWG was established in 2008. More helpful information and related Internet links may be found at http://www.igs.org/wg. For an overview of relevant GNSS biases, the interested reader is referred to (Schaer 2012).

2 Activities in 2017

- Regular generation of C1W–C1C (P1–C1) bias values for the GPS constellation (based on *indirect* estimation) and maintenance of receiver class tables was continued at CODE/AIUB.
- The final approval of the new **Bias-SINEX Format Version 1.00** by the IGS was a key achievement in 2017 (see also Section 6).

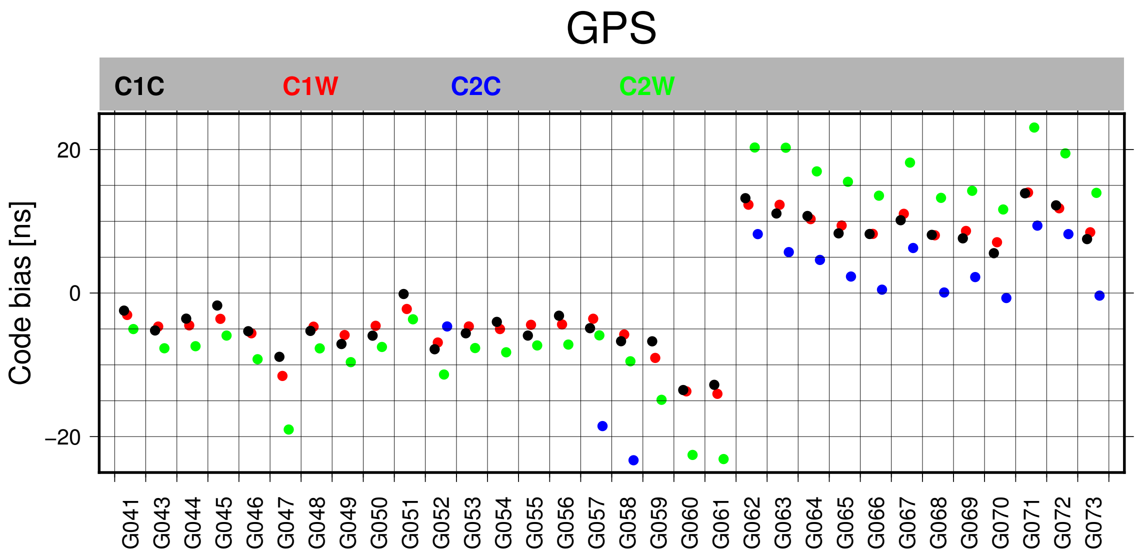

Figure 1: Observable-specific code bias (OSB) estimates for GPS code observable types (using the RINEX3 nomenclature) and GPS SV numbers, computed at CODE, for January 2018. Note that G041–G061 correspond to Block IIR, IIR-M; G062–G073 correspond to Block IIF satellite generations.

- At CODE, a refined GNSS bias handling to cope with all available GNSS systems and signals has been implemented and activated (in May 2016) in all IGS analysis lines. As part of this major revision, processing steps relevant to bias handling and retrieval were reviewed and completely redesigned. In 2017, further refinements could be achieved concerning bias processing and combination of the daily bias results at NEQ level. A daily updated 30-day sliding average for GPS and GLONASS code bias (OSB) values coming from a rigorous combination of ionosphere and clock analysis is made available in Bias-SINEX V1.00 at: `ftp://ftp.aiub.unibe.ch/CODE/CODE.BIA`
- It should be mentioned that the current GPS C1W-C1C DSB (P1-C1 DCB) product provided by CODE (specifically in the Bernese DCB and in a CC2NONCC-compatible format) corresponds to a converted extract from our new OSB final/rapid product line.
- Our new bias implementation allows to combine bias results at normal-equation (NEQ) level. We are thus able to combine bias results obtained from both clock and ionosphere analysis, and, moreover, to compute coherent long-term OSB solutions. This could be already achieved for the period starting with epoch 2016:136:00000 up to now. Corresponding long-term OSB solutions are updated daily (see GPS/GLONASS bias results shown in Figures 1 and 2).
- The tool developed for *direct* estimation of GNSS P1–C1 and P2–C2 DCB values is

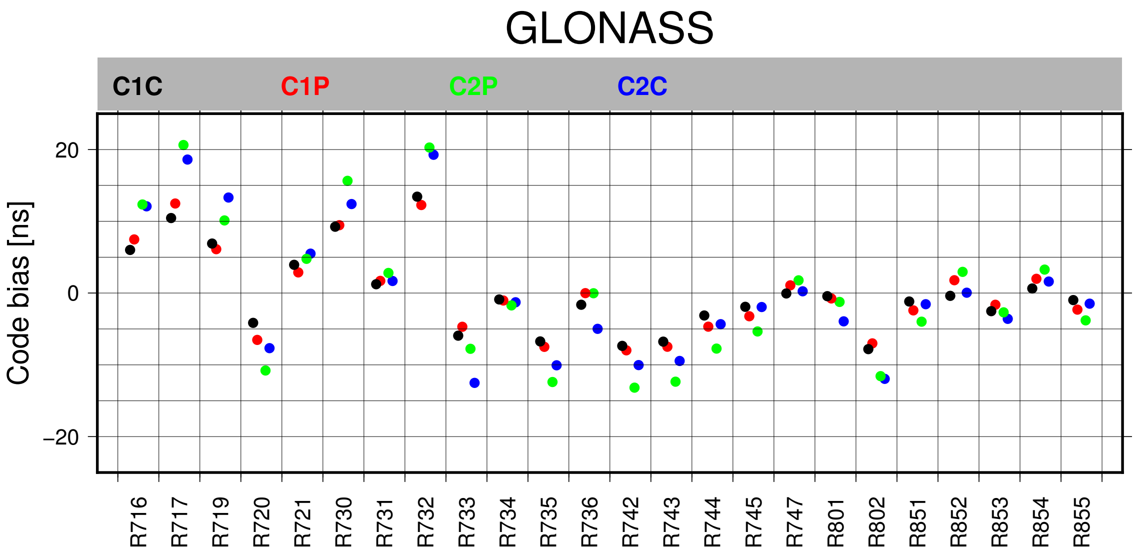

Figure 2: Observable-specific code bias (OSB) estimates for GLONASS code observable types (using the RINEX3 nomenclature) and GLONASS SV numbers, computed at CODE, for January 2018.

(still) used to generate corresponding GPS and GLONASS bias results on a daily basis.

- The ambiguity resolution scheme at CODE was extended (in 2011) to GLONASS for three resolution strategies. It is essential that *self-calibrating* ambiguity resolution procedures are used. Resulting GLONASS DCPB(differential code-phase bias) results are collected and archived daily.
- More experience could be gained concerning station-specific GLONASS-GPS intersystem translation parameters, which are estimated and accumulated as part of CODE's IGS analysis (but completely ignored for all submissions to IGS).
- CODE's enhanced RINEX observation data monitoring was continued. Examples may be found at:
  `ftp://ftp.aiub.unibe.ch/igsdata/odata2_day.txt`
  `ftp://ftp.aiub.unibe.ch/igsdata/odata2_receiver.txt`
  `ftp://ftp.aiub.unibe.ch/igsdata/y2017/odata2_d335.txt`
  `ftp://ftp.aiub.unibe.ch/igsdata/y2017/odata2_d335_sat.txt`
  Internally, the corresponding information is extracted and produced using metadata stored in an xml database (established in December 2014).
- This RINEX monitoring service is provided in addition for MGEX observation data (available in RINEX3 format). See: `ftp://ftp.aiub.unibe.ch/mgex/y2017`

3 Last Reprocessing Activities

In 2012: A complete GPS/GLONASS DCB reprocessing was carried out at CODE on the basis of 1990–2011 RINEX data. The outcome of this P1–C1 and P2–C2 DCB reprocessing effort is: daily sets, a multitude of daily subsets, and in addition monthly sets.

In 2016/2017: A GNSS bias reprocessing (for GPS/GLONASS) using the recently implemented observable-specific code bias (OSB) parameterization was initiated at CODE for 1994-2016 RINEX data. The outcome of this reprocessing effort are daily NEQs for GPS and GLONASS OSB parameters from both global ionosphere and clock estimation. A consistent time series of global ionosphere maps (GIMs) with a time resolution of 1 hour is an essential by-product of this bias reprocessing effort.

In 2017: 3-day combined ionosphere solutions were computed for the entire reprocessing period (back to 1994). The ionosphere (IONEX) results (for the middle day) of this computation effort were not yet made available to the public.

4 Computation of Coherent Long-Term GPS/GLONASS Code Bias Solution

The accumulated "bias-NEQs" from our 1994–2016 bias reprocessing in conjunction with those from our operational IGS processing allow us to compute a coherent long-term GPS/GLONASS code bias solution. Such a computation procedure could be successfully implemented. The bias combination procedure is executed on a daily basis thus yielding daily updates for our long-term GPS/GLONASS code bias solution. This NEQ-combined bias solution covers more than 24 years and provides one common datum over the entire period. This particular property is of great interest for those applications where long-term stability is crucial (e.g. for timing, or time transfer applications using GNSS).

The daily bias-NEQ results are re-aligned relying on the unique bias datum provided by our long-term bias solution. This re-alignment of all daily bias retrievals is done once a week. Examples of thus re-aligned time series are shown in Figure 3 for one selected GPS satellite (SVN G046).

A list of instantaneous discontinuities that could be collected as part of the implementation of the long-term code bias combination was an essential outcome. The epochs of this discontinuity list are then used to decide to which combination time window the daily NEQ contributions have to be referred to. Many of these epochs may be associated with a maintenance event as they were announced in GPS NANU messages. The first discontinuity in 2001 in Figure 3 may be attributed to such an event: NANU 2001120: SVN46 (PRN11) UNUSABLE JDAY 256/0030 - JDAY 256/0530.

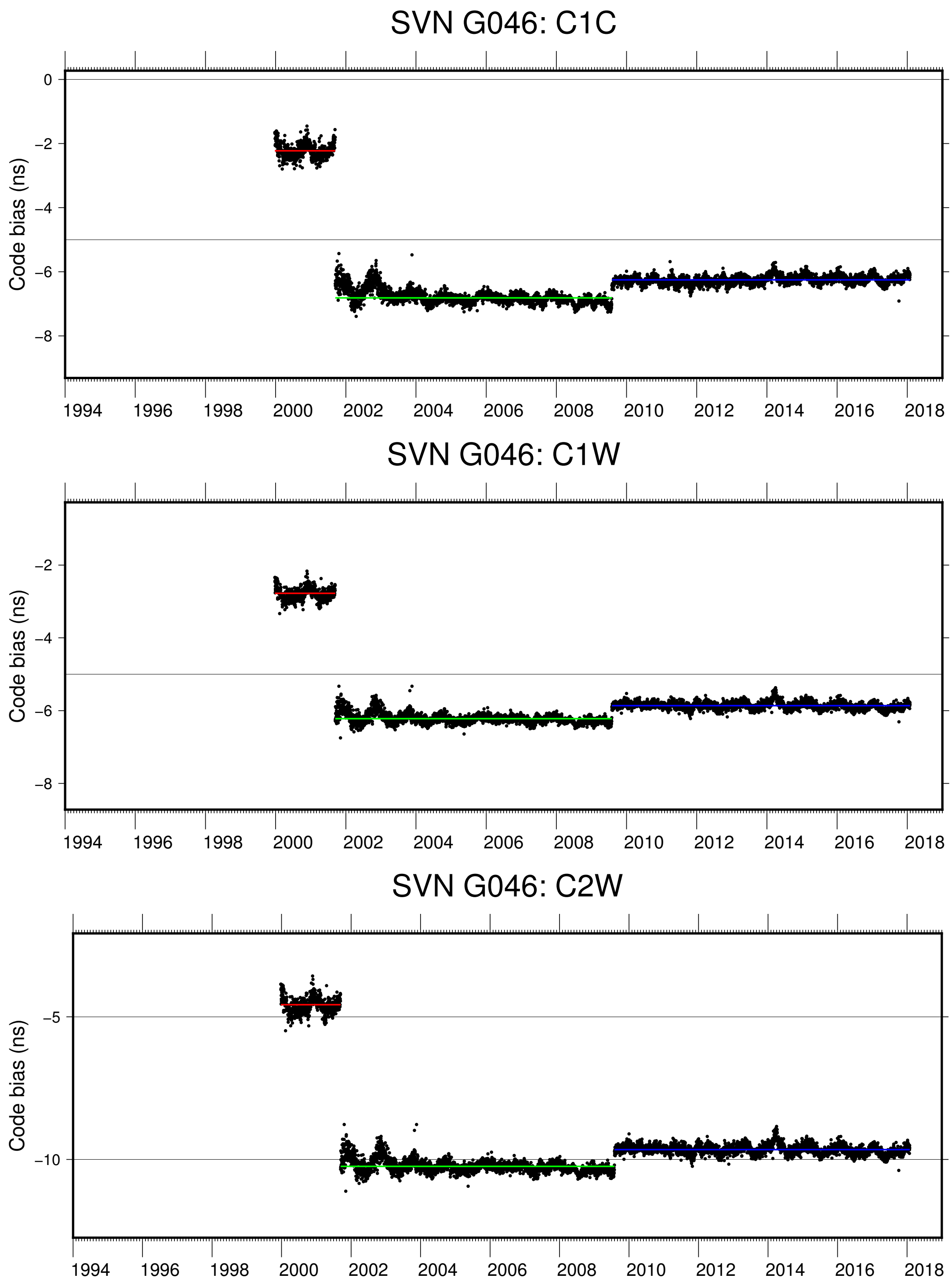

Figure 3: Time series of daily code bias (OSB) estimates for a selected GPS satellite (SVN G046) and various code observable types (C1C, C1W, C2W), computed at CODE on the basis of "bias-NEQs" from a dedicated reprocessing. Note that the daily results were realigned with respect to the combined bias solution (indicated with colored lines).

```
*-------------------------------------------------------------------------------
+BIAS/SOLUTION
*BIAS SVN_ PRN STATION__ OBS1 OBS2 BIAS_START____ BIAS_END______ UNIT __ESTIMATED_VALUE____ _STD_DEV___
 OSB  G063 G01           C1C       2018:030:00000 2018:031:00000 ns                -1.60616      0.00603
 OSB  G063 G01           C2C       2018:030:00000 2018:031:00000 ns                -3.65842      0.20465
 OSB  G063 G01           C1W       2018:030:00000 2018:031:00000 ns                -0.01049      0.00108
 OSB  G063 G01           C2W       2018:030:00000 2018:031:00000 ns                 0.01160      0.00109
 OSB  G063 G01           L1C       2018:030:00000 2018:031:00000 ns                -0.17676      0.00000
 OSB  G063 G01           L1W       2018:030:00000 2018:031:00000 ns                -0.17676      0.00000
 OSB  G063 G01           L2C       2018:030:00000 2018:031:00000 ns                -0.36450      0.00000
 OSB  G063 G01           L2W       2018:030:00000 2018:031:00000 ns                -0.36450      0.00000
 ...
-BIAS/SOLUTION
*-------------------------------------------------------------------------------
```

Figure 4: Example for a set of code and phase bias values for a GPS satellite (G063/G01) as included in a Bias-SINEX file.

5 Determination of Fractional Phase Biases for Undifferenced Ambiguity Resolution

First developments were made towards determination of fractional phase biases for *undifferenced* ambiguity resolution (AR) as they may be used for PPP-AR or simply Integer-PPP (IPPP), where between-satellite single differencing is commonly applied for AR.

A new software components in this working field is PHABIA, a dedicated program that is able to extract widelane (WL) or narrowlane (NL) fractional phase biases from PPP analysis results of a significant sample of IGS station data.

Following our pseudo-absolute (OSB) bias treatment, the retrieved WL and NL fractional phase biases may be finally mapped to a set of L1 and L2 phase biases that is consistent to the two particular linear combinations (LC): WL and NL.

Figure 4 illustrates how such a consistent set of code and phase bias values may be provided in a Bias-SINEX file. A user may just consider the given set of biases (in combination with a bias-consistent GPS clock product) for all involved code and phase observations (and accordingly derived LCs, such as Melbourne-Wübbena or ionosphere-free LC).

6 Bias-SINEX Format Version 1.00

A finalized draft version for the new Bias-SINEX Format (Version 1.00) was announced in (Schaer 2016b):

ftp://ftp.aiub.unibe.ch/bcwg/format/draft/sinex_bias_100_dec07.pdf

This format version has been developed on the basis of

- a first draft proposed and discussed at the IGS Bias Workshop 2015 in Bern, Switzerland,
- an updated draft prepared for the IGS Workshop 2016 in Sydney,
- substantial inputs from the IGS MGEX community (in particular from Oliver Montenbruck, DLR, Germany), and
- our experiences gained as part of the GNSS bias implementation performed at CODE.

The latest essential updates since the IGS Workshop 2016 included:

- Bias-SINEX was completely decoupled from the SINEX format and corresponding format descriptions.
- The previously used 2-digit year tag (YY) was generally replaced by a 4-digit year tag (YYYY) for all time tags (YYYY:DDD:SSSSS).
- Numerous bias (.BIA) example files could be prepared based on the new GNSS bias products generated at CODE.

The latest format document (and the entire format document history) may be found at:

http://www.biasws2015.unibe.ch/documents.html

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IGS Data Center Working Group Technical Report 2017

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1 Introduction

The IGS Data Center Working Group (DCWG) was established in 2002. The DCWG tackles many of the problems facing the IGS data centers as well as develops new ideas to aid users both internal and external to the IGS. The direction of the IGS has changed since its start in 1992 and many new working groups, projects, data sets, and products have been created and incorporated into the service since that time. The DCWG was formed to revisit the requirements of data centers within the IGS and to address issues relevant to effective operation of all IGS data centers, operational, regional, and global.

2 Recent Activities

Several recommendations were put forth at the 2016 IGS Workshop in Sydney Australia. Work continued during 2017 to address these activities:

- Encourage providers of RINEX V3 data to submit files (daily/hourly/high-rate) using V3 filename conventions to IGS data centers by the end of 2016. Until this task is implemented by the stations, GDCs should create the files using the V3 naming conventions.

  Results: Full integration of IGS RINEX V3 data, using RINEX V3 filename format, into the operational archives at the IGS Data Centers has been accomplished, starting with data from January 2016. DCs will review procedures to rename RINEX V3 data in the 8.3.Z filename format to RINEX V3 filename format and integrate older data into these directories as well. However, procedures for "renaming" files to use the V3 naming conventions have not yet been established at the GDCs.

- ACs and users in general should begin utilizing RINEX V3 data in the V3 filename format.

  Results: Unclear if all ACs are routinely using RINEX V3 data.

- Encourage DCWG to strive for implementation of XML Site Log Metadata System. In addition, encourage stakeholders to submit use cases (examples of the required interactions with the system) for XML Site Log Metadata System.

  Results: Significant work has been accomplished on this activity, particularly in GeodesyML. IGS participants are reviewing the format and providing feedback on its use and incorporating existing site log metadata into the schema. Regular telecons are held to discuss progress.

2.1 Meetings

A meeting of the IGS DCWG was held, in conjunction with the IGS Infrastructure Committee (IC) and RINEX Working Group, during the 2017 IGS Workshop in Paris France in July 2017. The integration of RINEX V3 data into the operational archives at the data centers has progressed well in the past year but work remains. The IC and IGS Network Coordinator continue to work with stations to submit data in RINEX V3 where appropriate. The following recommendations from the IGS DCWG were put forward at the Paris workshop:

- Provide recommendations from the DCWG for refinements to GeodesyML for Site Log metadata. Help is sought in promoting GeodesyML and its use in the IGS; everyone with the ability should be provide site log metadata in GeodesyML.
- Encourage interested DCWG participants to strive for implementation of the GeodesyML / IGS Site Log Metadata XML System by providing increased availability of GeodesyML formatted Site Log metadata and web services for GeodesyML metadata access.

2.2 RINEX V3 Integration

The parallel structure implemented at the IGS global data centers (GDCs) to support the Multi-GNSS Experiment (MGEX) has limited the motivation of the ACs to switch to using the RINEX V3 format. Integration of the two data archives promotes use of multi-GNSS data and the new format. The IGS IC developed the "RINEX V3 Transition Plan" to accomplish the integration and two IGS GDCs (CDDIS and IGN) began storing RINEX V3 data submitted using the V3 filenaming convention into the operational archives in early

2016.

Questions still to be addressed include how to handle RINEX V3 data not supplied in the new filename convention. DCs could use tools such as *gfzrnx* to create these files with long filenames at the DCs but getting the files from the station operators is preferred. The use of any "renaming" software at the DCs remains an open question.

The DCWG will continue to work with the IC on implementing naming software as well as using tools such as *anubis* to QC RINEX V3 data and supply the QC information through the data centers in summary/status files as has been done for data in RINEX V2 format.

2.3 Site Metadata Activities

Another area of interest for the IGS IC and DCWG involves metadata, particularly in the area of site logs. The IGS Central Bureau (CB) uses the Site Log Manager System for handling IGS site logs, which provides a basis for promoting the transmission of these logs in XML format. An XML/database management approach to site logs provides several advantages, such as rapid update of site log contents, utilization of consistent information across data centers, and availability of more accurate station metadata. The DCWG held email discussions to continue the collaboration begun in 2015. The 2015 discussions included adoption of GeodesyML to include the Site Log XML schema (GeodesyML is an application schema of the Open Geospatial Consortium GML standard). Based on teleconference discussions and following further discussions at the 2016 IGS Workshop, the team at Geoscience Australia completed the agreed-upon modifications to the Site Log XML schema and released GeodesyML 0.3. The current version is 0.4; GA is taking comments on their GitHub site for changes to be considered for version 0.5. Several groups are working towards implementation of GeodesyML Site Log metadata into their internal systems including GA, ROB and UNAVCO. GA has implemented GeodesyML into the production metadata system used for their GNSS CORS system, including using GeodesyML for machine-to-machine messaging. ROB is implementing GeodesyML into their new metadata system called M3G. UNAVCO has a working prototype for GeodesyML output from the IGS Site Log Manager system using Geoserver application server.

3 Future Plans

The DCWG will continue to coordinate with the IC, RINEX Working Group, and MGEX activity to fully realize the integration of data in RINEX V3 format into the main, operational archives at the IGS GDCs. The integration of these files with "long" RINEX V3 filenames into the operational archives is now routine for DCs and stations. Data centers will continue to test software for creating files using this V3 filename format to support the integration task for data prior to 2016. Once these procedures are finalized and validated/tested by the IC, DCs will provide files following the V3 naming convention in the operational archives for MGEX data prior to 2016.

Work on the site metadata activity will also continue. Geoscience Australia expects to be ready to begin working with external partners for machine-to-machine transfer of site log metadata via web services during 2018. Stand-alone software tools that can be used for conversion between text and XML formatted site logs that can be shared among all groups are in various stages of planning/development and will be required for broader adoption of GeodesyML for site log metadata.

Additional topics the WG hopes to address:

- Support of the IGS Infrastructure Committee: A major focus of the DCWG will be to continue its support the IC in its various activities to coordinate the resolution of issues related to the IGS components. These activities will address recommendations from the 2017 IGS Workshop as well as past workshops, including assessment and monitoring of station performance and data quality, generating metrics on these data.
- "Long" filename format for products: Currently ACs providing the differential code bias (DCB) product for MGEX use the AC-defined long filename. The DCWG work with the AWG to coordinate submission of other IGS products using "long" filename structure as has been previously proposed by IGS analysis groups.
- Compression: As per a recommendation from past IGS workshops, the DCWG will develop a plan for the introduction of a new compression scheme into the IGS infrastructure by evaluating tests of available tools, surveying the IGS infrastructure, making a recommendation on a new IGS compression scheme, and coordinating recommendations with the IC to develop implementation schedule. All data in RINEX V3 format using the V3 naming convention are supplied and archived in gzip format.

The next meeting of the DCWG is planned for the 2018 IGS workshop in Wuhan China (October 29 through November 02, 2018).

GNSS Monitoring Working Group Technical Report 2017

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1 Introduction

The Joint GNSS Monitoring Working Group was set up by the IGS Governing Board at its meeting in December 2016 in San Francisco in order to install, operate and further develop the IGS GNSS Monitoring and Assessment Pilot Project jointly with the International GNSS Monitoring and Assessment (IGMA) Task Force of the United Nations Office of Outer Space Affairs, International Committee on GNSS (UNOOSA-ICG).

The GNSS landscape is undergoing a fundamental transition with new satellite navigation systems being built up, existing systems being modernized and new signals and frequencies becoming available. Users will use these systems as one single system, benefiting from the enhancements contributed by the individual systems. To optimally exploit the benefits of multi-GNSS, users require homogeneous common monitoring of the performance of the individual constellation and signals, to verify service commitments are met and to ensure public confidence in GNSS service provision and iteroperability.

The ICG established the IGMA Task Force at the ICG-6 meeting in Tokyo in 2011, tasked to facilitate cooperation and information between providers and scientific organizations that engage in open service signal quality monitoring. The Task Force is co-chaired by ICG and IGS, members are GNSS system provider representatives. The ICG recommended at the ICG-10 meeting in Boulder 2015 that the IGMA Task Force and IGS initiate a joint Trial Project to demonstrate a global GNSS monitoring and assessment capability, utilizing existing resources and infrastructure and avoiding duplications.

Participation from non-IGS analysis groups, networks and data centers is invited to develop benchmarking between groups and generate analysis products, cross sharing between existing IGS functional streams and IGMA activities. Initially a limited number of parameters are proposed to be monitored to demonstrate the monitoring service and exercise it operationally. This will be followed by a broader set of parameters to be monitored as the system approaches permanent operations.

2 IGMA Pilot Project

At its meeting in December 2016 the IGS Governing Board installed the IGMA Working Group and Pilot Project and approved the Terms of Reference. Within the IGMA Task Force Terms of References for the IGMA-IGS Joint Trial Project were prepared defining the framework of the joint project and providing a draft for the list of parameters to be monitored and the common methodologies and algorithms to be applied. As the original idea to issue a joint call proved to be organizationally unrealistic, two parallel Calls for Participation were issued in Summer 2016, one by ICG addressing the GNSS Service Providers, the other by IGS addressing other interested groups withing and outside IGS.

Documents can be accessed at the following links

- Terms of Reference for IGMA-IGS Joint Trial Project:
`https://kb.igs.org/hc/en-us/article_attachments/210918728/ToR_IGMA-IGS_joint_trial_project_20160603V10.pdf`
- Annexes to IGMA-IGS ToR:
`https://kb.igs.org/hc/en-us/article_attachments/210918748/ToR_Annex_II_and_III_20160531_V3a.pdf`
- IGS IGMA WG Charter:
`https://kb.igs.org/hc/en-us/article_attachments/115006166207/Charter_MonPP_WG_2016_v10.pdf`
- IGS Call for Participation:
`https://kb.igs.org/hc/en-us/article_attachments/210918708/CfP_IGMA_for_IGS_160824.pdf`
- IGMA Call for Participation:
`https://kb.igs.org/hc/en-us/article_attachments/211054527/CfP_IGMA_for_ICG_Providers_20160815.pdf`

Tasks of the joint project are the determination of service parameters to monitor and the identification of gaps in current and planned monitoring and assessment methodologies, the proposal of an organizational approach avoiding duplication of existing activities, i.e., using existing infrastructure, and the exploration of methods to disseminate the products. With its Pilot Project IGS contributes to the joint project.

A short description of the Working Group and Pilot Project together with access to the

Terms of Reference is included in the IGS web site (`http://www.igs.org/wg`) and a mail exploder for the Working Group members is set up (`igs-igma@lists.igs.org`).

2.1 Tasks of the IGMA Pilot Project

The IGS CfP for the IGMA Pilot Project was issued in August 2016 seeking for groups that are interested to pool expertise as well as observing, data holding, and analysis capabilities [IGS Mail-7343]. The CfP specifically asked for contributing observing sites, data center capabilities, and monitoring analysis capabilities for monitoring a limited set of parameters (MAC, Monitoring Analysis Centers). In addition the call looked for groups ready to host a Monitoring Analysis Center Coordinator. The goal of the Pilot Project is the contribution to the joint IGS-IGMA Trial Project but also to engage new groups with the IGS.

Parameters of all existing navigation systems, i.e., the global navigation satellite systems GPS, GLONASS, Galileo, BeiDou and the regional system QZSS and later also NAVIC shall be monitored with the same methodology. Initial set of parameters to be monitored are the broadcast orbits and clocks, the SIS User Range Error, the SIS UTC Offset Error, and the PDOP for selected sites. The monitoring is initially performed off-line with a target to near-realtime and realtime. Goal is to get a common understanding of monitoring parameters and algorithms, but also to assess alternative parameters and methodologies.

The project follows IGS' open data and product policy. All provided data is publicly available, contributed stations are considered as IGS stations and included into the IGS network in cooperation with the Infrastructure Committee. Products generated for the project are first exchanged and discussed within the Pilot Project contributors and published only after agreement with the IGMA Task Force.

The Pilot Project terminates if it demonstrated the ability to monitor desired parameters and to generate publicly available useful products, if processes are defined for defining new parameters and for registering new Analysis Centers, if an organizational structure within or outside IGS is established for operating a GNSS Monitoring and Assessment Service, if IGMA or IGS is ready to implement a fully operational monitoring service, or if the project determined that such a service is not feasible.

2.2 Proposals

A total of 17 proposals were submitted by groups all over the world. Table 1 lists the participants in the project. 10 of the 17 groups are ready to provide additional monitoring stations, 4 provide data center capabilities while 12 groups are contributing to the analysis and product generation. About half of the participants were not directly associated to the IGS before. The pilot project was thus already successful in attracting new groups and expertise for the IGS. ESOC/ESA is ready to host the analysis coordination and submitted a corresponding proposal. Monitoring Analysis Center Coordinator for the Pilot Project is Tim Springer, former Analysis Center Coordinator of the IGS.

Table 1: Participants and contributions (stations, data center, analysis)

Nr	Participants	Sta	DC	Anal
1	Richard Langley, University of New Brunswick, Canada	X		
2	Rafal Sieradzki, Pawel Wielgosz, University of Warmia and Mazury in Olsztyn, Poland	X		
3	Sungpil Yoon, Kevin Choi, National Geodetic Survey, Silver Spring, USA	X		
4	Yuki Hatanaka, Geospatial Information Authority of Japan (GSI), Tsukuba, Japan	X		
5	Carey Noll, CDDIS, GSFC, NASA, Greenbelt, USA		X	
6	Anna Maria Baron Isanta, Joel Grau Bellet, Enrest Bosch Llopart, Institut Cartogràphic i Geològic de Catalunia, Spain	X	X	X
7	Joao Monico, Universidade Estadual Paulista, Brasil	X		X
8	Jan Douša, Pavel Václavovic, Pavel Novák, Research Institute of Geodesy, Topography and Cartography, Czech Republic			X
9	Peter Steigenberger, Oliver Montenbruck, Deutsches Zentrum für Luft- und Raumfahrt, Oberpfaffenhofen, Germany			X
10	Furqan Ahmed, Srinivas Bettadpur, The University of Texas at Austin, Austin, USA	X		X
11	Yanming Feng, Charles Wang, Queensland University of Technology, School of electrical Engineering and computer science, Melbourne, Australia			X
12	Zhiguo Deng, GFZ German Research Centre for Geosciences, Potsdam, Germany			X
13	Werner Enderle, Ignacio Romero, Tim Springer, ESA/ESOC, Darmstadt, Germany	X	X	X
14	Qile Zhao, Min Li, Chuang Shi, Wuhan University, GNSS Research Center, Wuhan, China	X	X	X
15	Junping Chen, Shanghai Astronomical Observatory, Tonji University, Shanghai, China	X		X
16	Irma Rodriguez Perez, Guillermo Tobias Gonzalez, GMV, Madrid, Spain			X
17	Ahmed Mohamed Ali, Dubai Municipality, United Arab Emirates			X
18	Virendra Patel, Sardar Vallabhbhai National Institute of Technology, Surat, India		X	X

Table 2 lists the individual contributions of the participants to the analysis effort, including one MAC already proposing monitoring of parameters for IRNSS.

The call remains open and interested groups can join the Pilot Project at any time.

Table 2: Analysis proposals

Proposal Nr	6	7	8	9	10	11	12	13	14	15	16	17	18
Parameters													
Broadcast orbits	x		x	x	x	x	x	x	x	x	x	x	x
Broadcast clocks	x		x	x	x	x	x	x	x	x	x	x	x
SIS User Range Error	x		x	x	x	x		x	x	x	x	x	
SIS UTC Offset Error	x				x	x		x	x	x	x	x	
PDOP for defined sites	x	x	x		x	x		x	x	x	x	x	x
for System													
BeiDou	x		x	x		x	x	x	x	x	x	x	
Galileo	x	x	x	x	x	x	x	x	x	x	x	x	
GLONASS	x		x	x	x		x	x	x	x	x	x	
GPS	x	x	x	x	x	x	x	x	x	x	x	x	
QZSS			x			x	x	x	x	x	x	x	
IRNSS													x

2.3 Requirements

Several requirements have to be fulfilled as a basis for the project, mainly related to reference products and recording of broadcast information. Monitoring parameters shall be compared with high precision and consistent IGS orbit and clock estimates of all GNSS systems. However, official IGS combined orbit and clock products are only available for GPS while for GLONASS only combined orbit products are available. For the emerging systems AC orbit and clock products are available within the MGEX Pilot Project, but no combined products are available. The available AC solutions have thus to be reviewed and reference orbit and clock products for each of the systems have to be defined or generated. Eventually a consistent combination of MGEX products is needed.

Broadcast ephemerides typically reflect phase center location of the transmitter for a certain frequency whereas IGS products refer to the center of mass. For a consistent generation of products an agreed-on center of mass to phase center vector has to be defined. In addition attitude information is necessary. These information shall be defined in interaction with the system providers.

A serious monitoring of service availability and integrity imposes substantially higher needs on the database of broadcast ephemeris data. Among others, receiver specific representation details (e.g. floating point resolution, bit flags, etc.) must be handled, records must be compared and conflicts be resolved as part of a screening process, a full global coverage (and adequate redundancy) must be guaranteed to make sure that all navigation messages ever transmitted by a satellite are also received and made available in the archive, all relevant parameters in the binary navigation messages must be made available in the data base, information on the transmission time must be properly maintained to achieve traceability of the time of first reception within the network, and last but not least, all navigation message types must be properly supported.

The current RINEX navigation message format needs to be extended as it is, e.g., incomplete concerning GLONASS navigation parameters such as the 'FT' parameter that provides the predicted satellite user range accuracy. This quantity is of major relevance for assessing the service availability and integrity. It does not support the full set of new navigation message formats (such as CNAV, CNAV2, etc.) that have or are about to become available with the ongoing GNSS system evolution. RINEX focuses on the provision of selected key parameters, primarily orbit and clock information, but does not give a full picture of what has been transmitted at a given time. Only a full storage of the raw binary navigation message bit stream would allow for an unbiased and traceable assessment of the data made available to the user.

The newly arising needs in this area have to be carefully assess to establish a robust, reliable, and quality broadcast ephemeris archive. Specifically it has to be decided on how to specify and improve the quality of a cumulative broadcast ephemeris product based on existing data sources and formats, how to extend the RINEX standard for decoded navigation messages, and how to define a new standard for raw navigation messages (within or outside RINEX) and how to setup data collection, screening and archiving of such data. The discussions have to engage other bodies in the IGS apart from the IGMA WG such as the Infrastructure Committee, the RINEX WG, Multi-GNSS WG, and the Data Center WG.

Finally, exchange formats will have to be defined. A subgroup of the IGMA Task Force focusing on formats, lead by Shuli Song and John Lavrakas was formed with Nacho Romero representing the IGS.

All tools developed in the project for monitoring and performance assessment will have to be compliant with the Terms of Reference of the IGMA-IGS Joint Trial project while allowing flexibility for exploring alternative directions.

2.4 Initial Results

The Pilot Project was kicked-off at the IGS Workshop in Paris in July 2017 and an initial campaign was defined. The participants were asked to provide monitoring products for the week of August 2-8, 2017. The goal was to generate initial products to initiate discussion on different methodologies, algorithms, formats, without yet specifying details such as data origin, reference products, sampling, formats, etc.

Initial products were submitted by five groups and more are in preparation. A summary of the submitted products is given in Table 3. As expected the products are heterogeneous in terms of data sources and reference products used, algorithms and methodology employed, sampling, frequency, and format. This was expected and discussion on homogenization

Table 3: Inital products **complete???**

MAC	#	Parameters	System	Sampl.	Freq.	Format
DLR	9	R/T/N/C, dr WUL, GPS: CNAV LNAV, GAL: FNAV INAV	GPS, GLO, GAL, BDS	15 min	weakly	Table, plots
		SISRE 95%, SISRE rms, orb, clk		weekly	weekly	
GFZ	5	R/T/N/C, SISRE, rms per sat	GPS, GLO, GAL, BDS	15 min	daily	Table
GMV	9	R/T/N/C, rms, std, mean, SISURE,age, UTC-offset	GPS	15 min	daily	Table, plots
		nsat, PDOP				2x2 grid
Pecny	7	D/R/T/N/C, mean, rms, std	GPS, GLO, GAL, BDS	15 min	daily	Table
		SISURE, PDOP				10x10 grid
UTCSR	8	X/Y/Z/R/T/N/C, SISRE, rms	GPS, GLO, GAL	10 min	daily	Table

can start on the basis of existing products and gained experience of the groups.

3 Next Steps

The analysis of the submissions for the initial test week is underway and a new campaign with more specific requests is being defined. Detailed prescriptions for this second campaign will be specifically based on the parameters and methodologies defined in the Terms of Reference of the IGMA-IGS Joint Trial Project in order to obtain comparable products from each group and to start discussions about the details of the algorithms and the common understanding of parameters.

Additional steps to be performed are the review of available orbit and clock solutions for defining reference products and the review of available tools. Discussions on a traceable raw bits navigation message data base supporting all GNSS and extension of RINEX standard for decoded navigation messages including non-standard data broadcast have to be initiated together with the RINEX WG, the Multi-GNSS WG, the Data Center WG, and the Infrastructure Committee.

Initial results shall be available for the internal IGMA Task Force Workshop planned in May 2018 at the Galileo Reference Centre in Noordwijk, The Netherlands.

Multi–GNSS Working Group Technical Report 2017

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1 Introduction

The main activity of the Multi-GNSS Working Group (MGWG) is the Multi-GNSS Pilot Project (MGEX). MGEX finally aims at the integration of the evolving global and regional satellite navigation systems Galileo, BeiDou, QZSS, and NavIC (IRNSS) into the IGS data archives and operational products. Whereas the integration of the multi-GNSS observation data was already finished in 2016, improving the product quality of the emerging GNSS to achieve the same quality as for the legacy GPS and GLONASS is still an ongoing process. The membership of the MGWG has not changed in 2017. The members are representatives of the analysis and data centers as well selected specialists contributing to the goals of the MGWG.

2 GNSS Evolution

The satellite launches of the evolving systems Galileo, BeiDou, and QZSS in 2017 are listed in Table 1. Three 2nd generation QZSS satellites have been launched in 2017, two in inclined geosynchronous orbit like QZS-1 and one in geostationary orbit. Operational services of QZSS are expected to start in 2018.

The launch of a replacement satellite for NavIC (IRNSS-1H) failed in August 2017 as the heat shield of the launcher did not separate. This satellite should have replace IRNSS-1A suffering from a failure of all three rubidium clocks. The causes for problems with the Galileo rubidium as well as passive hydrogen maser clocks have been identified and the clocks still on ground have been refurbished prior to the launch in December 2017. This

Table 1: GNSS satellite launches in 2017.

Date	Satellite	Type
01 Jun 2017	QZS-2	IGSO
19 Aug 2017	QZS-3	GEO
09 Oct 2017	QZS-4	IGSO
05 Nov 2017	BeiDou-3 M1 and M2	MEO
12 Dec 2017	Galileo FOC FM-15/16/17/18	MEO

second Galileo launch with Ariane 5 delivered another four satellites into orbit. A further quadruple launch is planned for 2018.

Whereas five test satellites for BeiDou-3 (denoted as BeiDou-3S) have already been launched in 2015/6, 2017 marks the launch of the first two MEO satellites for the operational constellation. An ICD for the BeiDou-3 open service signals B1C and B2a has been published in August 2017 (China Satellite Navigation Office 2017).

3 Network

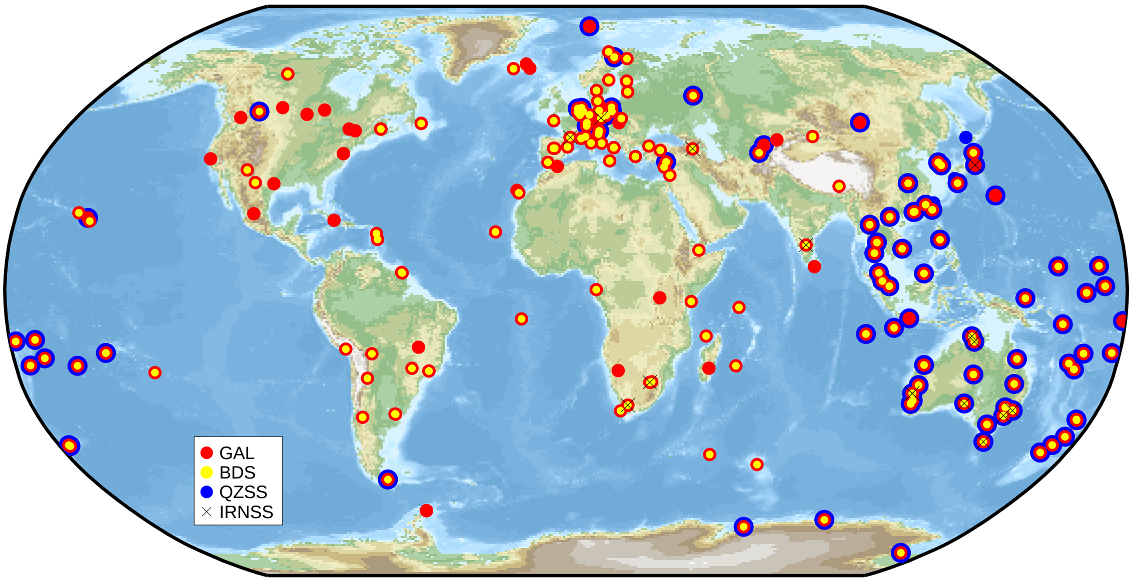

Figure 1: Distribution of IGS multi-GNSS stations supporting tracking of Galileo (red), BeiDou (yellow), QZSS (blue), and IRNSS (black crosses) as of December 2017.

As of December 2017, 218 out of 505 IGS tracking network stations were multi-GNSS stations providing their observations in RINEX 3 format. 13 of these stations were dormant,

Table 2: Analysis centers contributing to IGS MGEX.

Institution	Abbr.	GNSS
CNES/CLS	grm	GPS+GLO+GAL
CODE	COD0MGXFIN	GPS+GLO+GAL+BDS+QZS
GFZ	gbm	GPS+GLO+GAL+BDS+QZS
JAXA	JAX0MGXFIN	GPS+GLO+QZS
TUM	tum	GAL+QZS
Wuhan University	wum	GPS+GLO+GAL+BDS+QZS

i.e., data are missing since more than three weeks. In addition, data of five MGEX experimental stations are available that did not meet the requirements of the IGS site guidelines but are still important for experimental applications. Real-time data are available from the BKG MGEX and IGS-IP casters for 127 multi-GNSS stations.

Triple-frequency BeiDou-3S observations are currently only provided by Javad TRE_3 receivers, whereas Septentrio PolaRx5 receivers provide dual-frequency (B1/B3) tracking of these satellites. However, implementation of the new BeiDou-3 signals in the RINEX 3 format definition is still pending.

4 Products

The MGEX analysis centers and the GNSS covered by their products are listed in Table 2. The number of analysis centers has not changed compared to 2016. However, JAXA included GLONASS starting with the switch to a new product line in April 2017. Since GPS week 1962, CODE provides a 30 s clock solution. These new CODE and JAXA products are indicated with long file names which are discussed in Sect. 5. In addition to the well established data centers at CDDIS and IGN, MGEX products are also available from the new IGS data center of the European Space Astronomy Centre (ESAC) of the European Space Agency (ESA).

In the following, selected publications based on MGEX data and products or relevant for multi-GNSS processing are discussed. Sośnica et al. (2017) validated the CODE MGEX Galileo orbits with satellite laser ranging (SLR). They found systematic biases in the order of 2 – 5 cm and RMS values between 4 and 5 cm.

Xie et al. (2017) show first results of the precise orbit and clock determination of BDS-3. They could achieve an orbit accuracy evaluated by SLR of 1 – 3 dm. Zhang et al. (2017) analyzed the BDS-3 navigation signals and demonstrate that BDS-3 does not suffer from satellite-induced elevation-dependent code variations like the BDS-2 satellites (Wanninger and Beer 2014). An alternative correction model for these BDS-2 pseudorange variations was developed by Zou et al. (2017) with model coefficients for each individual satellite and frequency. Zhao et al. (2018) showed that BDS-3 satellites do not enter orbit normal mode for elevations of the Sun above the orbital plane $|\beta| < 4°$. Dilssner (2017) used the reverse PPP technique for attitude analysis of the latest BDS-2 satellite, namely BeiDou IGSO-6, that does also not enter orbit normal mode. Dilssner (2017) developed a simple yaw attitude model for IGSO-6 and identified two other BDS-2 satellites not utilizing orbit normal mode since October 2016 and March 2017, respectively.

Dedicated box-wing models for QZS-1 were developed by Montenbruck et al. (2017) and Zhao et al. (2017). Both models provide a RMS consistency with SLR better than 10 cm. Rajaiah et al. (2017) developed a dedicated orbit model for for the Indian Regional Navigation Satellite System (IRNSS) which is currently not covered by the MGEX products. Based on C-band ranging, they could achieve a few meter orbit precision and SLR residuals on the few decimeter level.

Steigenberger et al. (2017) measured the transmit power of GPS, GLONASS, Galileo, and BeiDou-2 satellites with a 30 m high-gain antenna. The transmit power is required for the computation of the antenna thrust that can alter the orbital radius by up to 3 cm depending on transmit power, mass, and orbital radius of the satellite. The transmit power of current IGS model (IGS 2011) that covers only GPS was found to be too large by about 40 %.

Li et al. (2017) estimated Differential Code Biases (DCBs) for Galileo and found an agreement on the 0.22 ns level with the corresponding MGEX estimates. For BeiDou, the RMS of the DCBs determined by Fan et al. (2017) and the MGEX DCB product is with 0.39 ns significantly higher.

Guo et al. (2017) assessed the performance of MGEX products for precise point positioning (PPP). They achieved RMS values of kinematic PPP position estimates of 2.0 cm for the North, 4.9 cm for the East, and 5.3 cm for the height component utilizing GPS, GLONASS, Galileo, and BeiDou. In a study of Wuhan University, the long-term variation of signal-in-space range errors of the BeiDou-2 system was assessed based on MGEX cumulative broadcast ephemerides and precise orbit clock products (Wu et al. 2017).

5 Long Product File Names

Starting with 2017, two analysis centers (CODE and JAXA) provide their products with long file names which are inherited from the RINEX 3 naming scheme. The DCB products of CAS and DLR are already provided with long file names since 2015. This new file naming allows for a proper distinction of legacy and MGEX products for the different product lines (ultra-rapid, rapid, and final products). The file name is composed of different fields providing information about analysis center, product version, campaign/project, product type, start epoch, sampling, content type, and format:

AAAVPPPTTT_YYYYDDDHHMM_LEN_SMP_CNT.FMT[.*]

Field	length	content
AAA	3 characters	analysis center abbreviation
V	1 character	version/solution identifier
PPP	3 characters	campaign/project specification
TTT	3 characters	type specification, e.g., ULT, RAP, FIN
YYYYDDDHHMM	11 digits	product start epoch
LEN	3 characters	intended (nominal) product period
SMP	3 characters	temporal resolution
CNT	3 characters	content type
FMT	3 characters	file format
	1 or 2	compression method extension, Z or gz

So far, only the version identifier 0 is used within MGEX whose project specification is MGX. The following content types are currently provided within MGEX

- CLK receiver and/or satellite clock parameters
- DCB differential code biases
- ERP Earth rotation parameters
- ORB satellite orbits
- OSB observable-specific signal bias
- SOL variance/covariance information or normal equations

using these file formats:

- BIA bias SINEX
- BSX bias SINEX
- CLK clock RINEX
- ERP IGS ERP format
- SNX Solution INdependent EXchange (SINEX) format
- SP3 Special Product 3 (SP3) orbit format

As an example, CODOMGXFIN_20173360000_01D_05M_ORB.SP3 denotes a final MGEX orbit file in SP3 format of the CODE analysis center covering one day (day of year 336/2017) with 5 min sampling.

6 GNSS Satellite Metadata

Knowledge about satellite metadata like antenna phase center position is crucial for a full exploitation of GNSSs. An IGS white paper on satellite and operations information for generation of precise GNSS orbit and clock products has been published by Montenbruck

(2017) and passed to the International Committee on Global Navigation Satellite Systems (ICG).

Galileo FOC metadata were published by the European Global Navigation Satellite Systems Agency (GSA) on 6 October 2017 (European GNSS Service Center 2017) following the earlier publication of IOV metadata. The Cabinet Office (CAO), Government of Japan, published QZSS satellite information (Cabinet Office 2017a, b, c, d) for all QZSS satellites in orbit. CAO is also the first provider publishing operational history information for QZS-1 (Cabinet Office 2017e) including date and time of attitude mode changes, date of reaction wheel unloading, date, time, duration and velocity change of orbit maintenance maneuvers as well as the post-maneuver mass. Publication of optical properties as well as operational history information for the other QZSS satellites is planned for 2018. Metadata not published so far for Galileo or QZSS include transmit antenna gain pattern, which are essential for the determination of the transmit power (Steigenberger et al. 2017).

In order to be able to store and exchange the GNSS satellite metadata in a standardized format, an extension of the solution independent exchange (SINEX) format Rothacher and Thaller (2006) has been developed. A first draft of this satellite metadata extension was distributed within the MGWG in November 2017 and covers the following new SINEX blocks:

- Satellite designations (static): SVN, COSPAR ID, satellite catalogue number, Block
- PRN assignment
- GLONASS frequency channel
- Spacecraft mass
- Center-of-mass position
- Equipment positions: GNSS transmit antennas, laser retroreflector array, ...
- Transmit power
- Yaw angle information for GPS satellites

Consolidation of the format and the content is currently in progress.

Acronyms

BKG Bundesamt für Kartographie und Geodäsie

CAS Chinese Academy of Sciences

CDDIS Crustal Dynamics Data Information System

CLS Collecte Localisation Satellites

CNES Centre National d'Etudes Spatiales

CODE Center for Orbit Determination in Europe

DLR Deutsches Zentrum für Luft- und Raumfahrt

GFZ Deutsches GeoForschungsZentrum

JAXA Japan Aerospace Exploration Agency

TUM Technische Universität München

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IGS Reference Frame Working Group Technical Report 2017

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1 Introduction

After a brief overview of the operational IGS SINEX combination results in 2017 (Section 2), this report reviews the current status of the newly adopted IGS14 reference frame, with a particular focus on the predictive quality of the associated post-seismic deformation models (Section 3).

2 Operational SINEX combinations

Figure 1 shows the WRMS of the AC station position residuals from the daily IGS SINEX combinations of year 2017, i.e. the global level of agreement between the AC and IGS combined station positions once reference frame differences have been removed. The WRMS of the AC station position residuals have remained at similar levels as in the previous years, with two notable exceptions:

- The WRMS of JPL's residuals have been higher since GPS week 1934, when all ACs except JPL switched from the IGS08/igs08.atx to the new IGS14/igs14.atx framework. Note that JPL solutions have been included for comparison only in the IGS SINEX combinations since then.
- The WRMS of ESA's residuals have gradually increased in Up since about GPS week 1971 and in North since about GPS week 1979. The causes of these increases are currently being investigated.

The AC Earth Orientation Parameter (EOP) residuals from the IGS SINEX combinations of year 2017 (Figures 2 and 3) exhibit similar features as in the previous years.

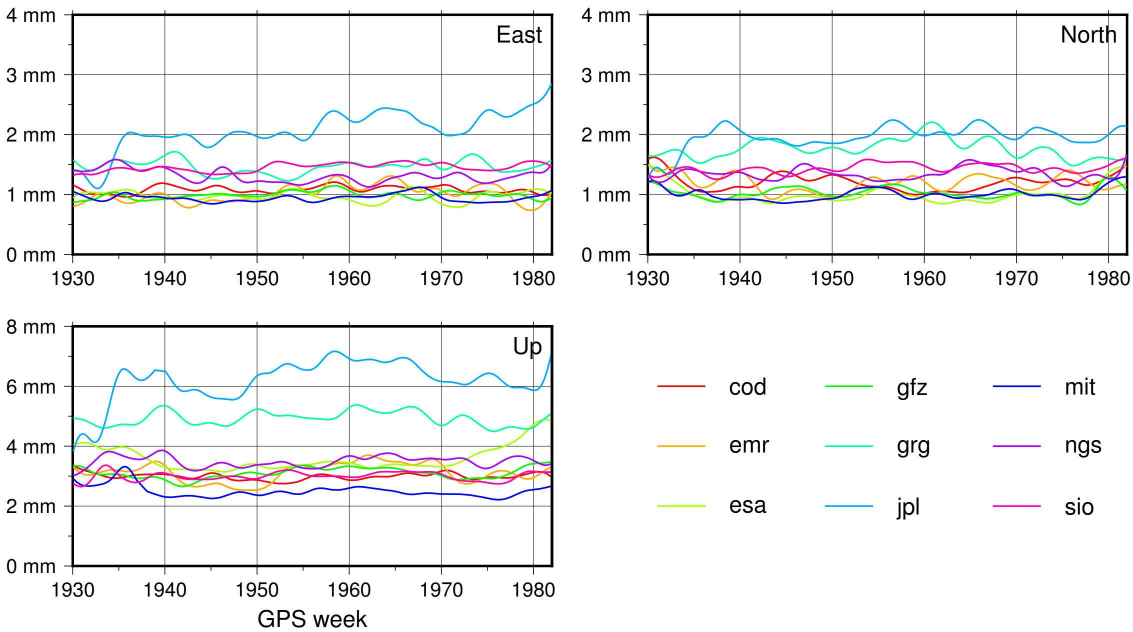

Figure 1: WRMS of AC station position residuals from the 2017 daily IGS SINEX combinations. All time series were low-pass filtered with a 10 cycles per year cut-off frequency.

3 Status of the IGS14 reference frame

Starting with GPS week 1934 (January 29, 2017), a new reference frame, IGS14, was adopted by the IGS together with an updated set of ground and satellite antenna calibrations, igs14.atx (IGSMAIL-7399). The new IGS14/igs14.atx framework replaces the previous IGS08/igs08.atx framework that had been used since GPS week 1632 (April 17, 2011). Figure 4 shows the numbers of reference frame stations available in recent daily IGS combined solutions, as well as the RMS of the residuals from 6-parameter transformations between the daily IGS combined solutions and the reference frame in use. The switch to IGS14 on week 1934 is marked by a clear increase in the number of available reference frame stations and a clear decrease of the transformation residuals, indicating an improvement in the precision of the alignment of the IGS daily solutions to the reference frame. Since then, both the number of available reference frame stations and the transformation residuals have remained at fairly stable levels. An update of the IGS14 reference frame does thus not seem necessary for now.

Like ITRF2014 (Altamimi et al. 2016), IGS14 includes post-seismic deformation (PSD) models for some stations. Those models were fitted to data up to GPS week 1831 (14 February 2015) and are now extrapolated by nearly 3 years. One can therefore wonder whether the ITRF2014/IGS14 PSD models are still able to accurately predict current station positions, or start diverging from them. Some of the ITRF2014 PSD models are

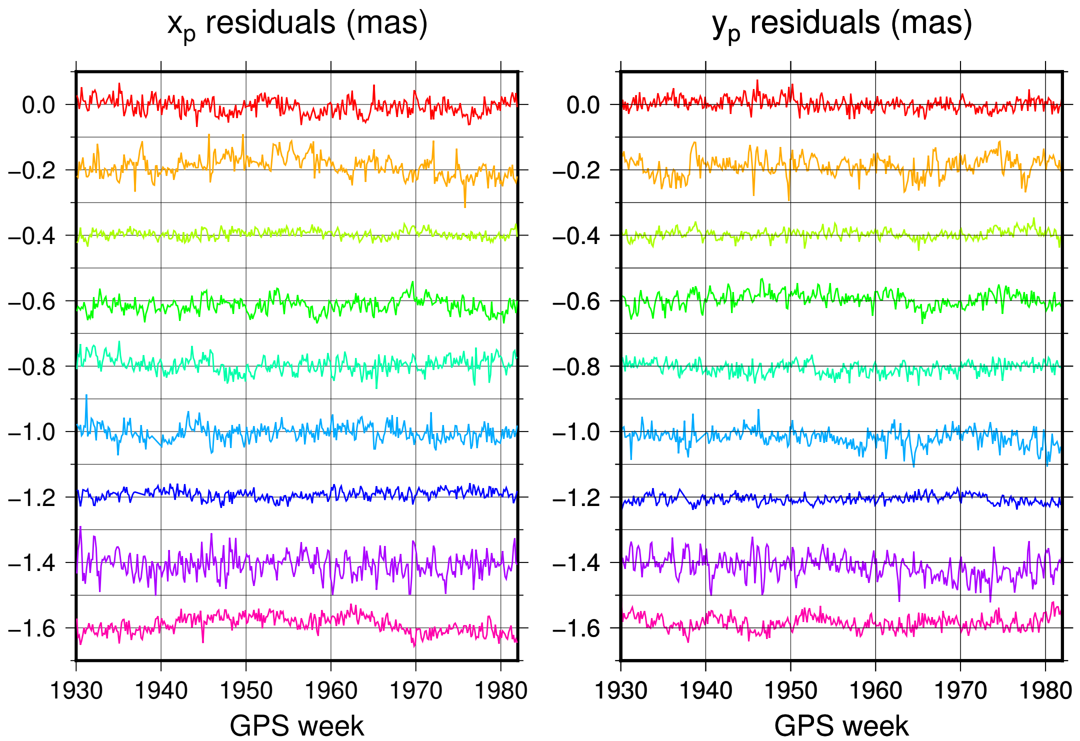

Figure 2: AC pole coordinate residuals from the 2017 daily IGS SINEX combinations. The individual AC time series have been shifted by multiples of 0.2 mas for clarity.

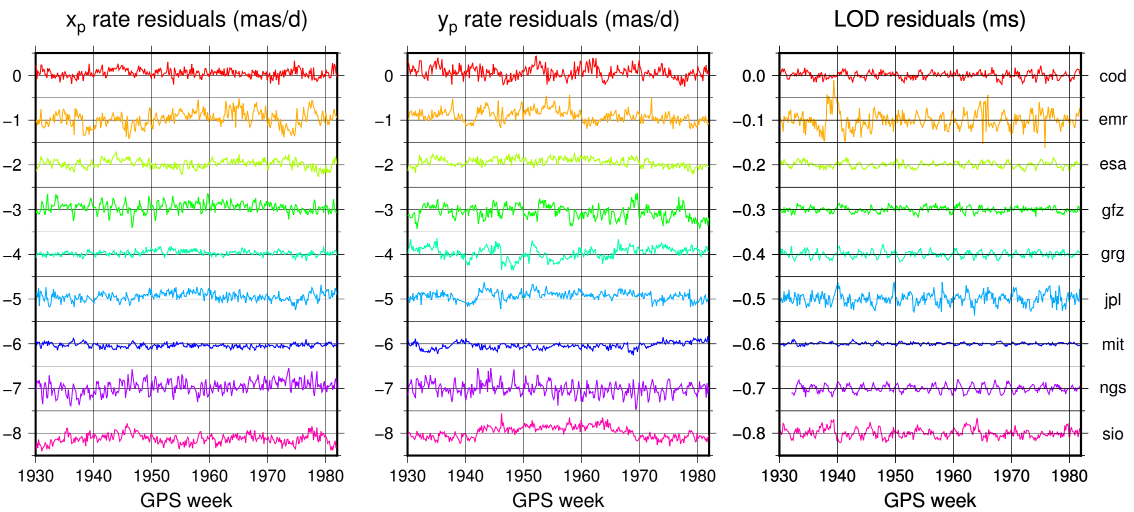

Figure 3: AC pole rate and LOD residuals from the 2017 daily IGS SINEX combinations. The individual AC time series have been shifted by multiples of 1 mas/d and 0.1 ms for clarity.

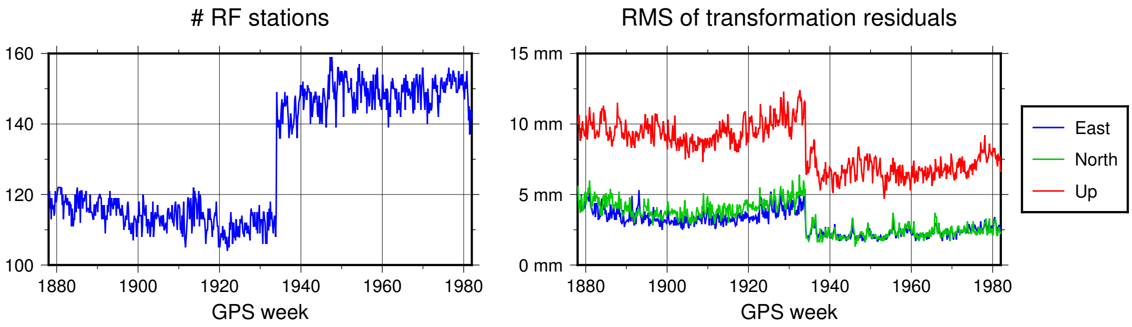

Figure 4: Left: Number of reference frame stations available in the daily IGS combined solutions of years 2016-2017. Right: RMS of the residuals from 6-parameter transformations between the daily IGS combined solutions and the reference frame in use.

actually diverging from current station positions (Rebischung and Altamimi 2017). This is particularly true for stations with post-seismic relaxation episodes that started shortly (i.e. a few years) before the end of the ITRF2014 input data. The selection of the IGS14 stations among all ITRF2014 GNSS stations however took the formal errors of the PSD models into account, precisely to avoid fast-growing extrapolation errors (Rebischung and Schmid 2016). To verify that the PSD models of the selected IGS14 stations do not diverge from their actual position time series, we plotted in Figure 5 the differences between the IGS daily station position time series of the IGS14 stations and their propagated IGS14 coordinates. IGS14 stations without PSD models are shown in cyan while IGS14 stations with PSD models are shown in red. It can be seen that the extrapolation errors for IGS14 stations with PSD models remain for now at a comparable level as for the IGS14 stations without PSD models. Users can therefore continue to rely on the PSD models provided with IGS14. Remember however that this does not hold for all ITRF2014 PSD models

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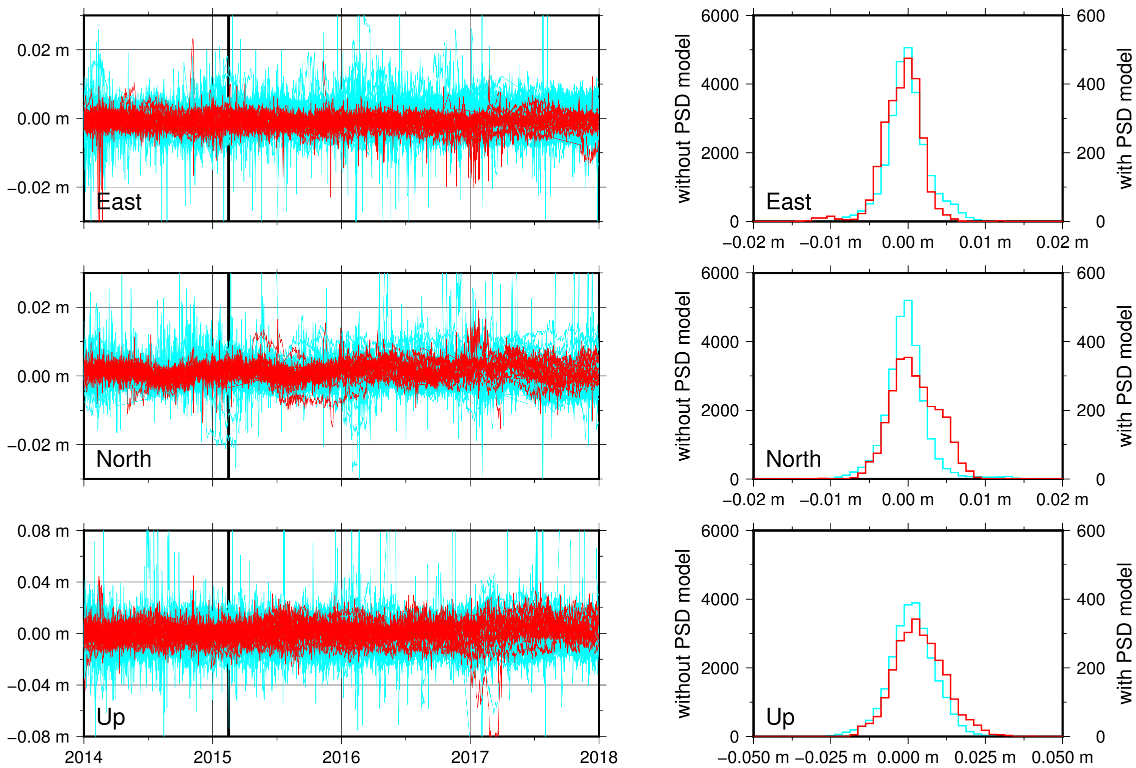

Figure 5: Left: Number of reference frame stations available in the daily IGS combined solutions of years 2016-2017. Right: RMS of the residuals from 6-parameter transformations between the daily IGS combined solutions and the reference frame in use.

IGS Realtime Service Technical Report 2017

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1 Introduction

The Real Time Service (RTS) expands the capacity of the International GNSS Service (IGS) to support applications requiring real-time access. It utilises a global receiver network and provides infrastructure for data and product dissemination. Analysis products include individual Analysis Centres as well as combination solutions. There is a large variety of potential applications for the service with a strong focus on scientific and educational applications.

In the caster registration process additional data about the users and their purposes are collected. Figure 3 shows users affiliations and applications for the CDDIS caster at NASA. Although is no distinction between the real time observations and products the strong support of the IGS RTS for science and education becomes obvious. But there is also a significant amount of commercial users and applications.

2 Observation network and real time data centers

The IGS-RTS is based on a global network of IGS stations providing data streams to the RTS observation broadcasters. All stations are operated by a large number of contributors on a best effort basis. There are several observation broadcasters in operation including the first level global casters at BKG, CDDIS and IGS Central Bureau (Figure 1, Table 1). All casters require individual registration on their webpages. Since IGS supports open data standards all casters provide data streams following the RTCM standard. The IGS

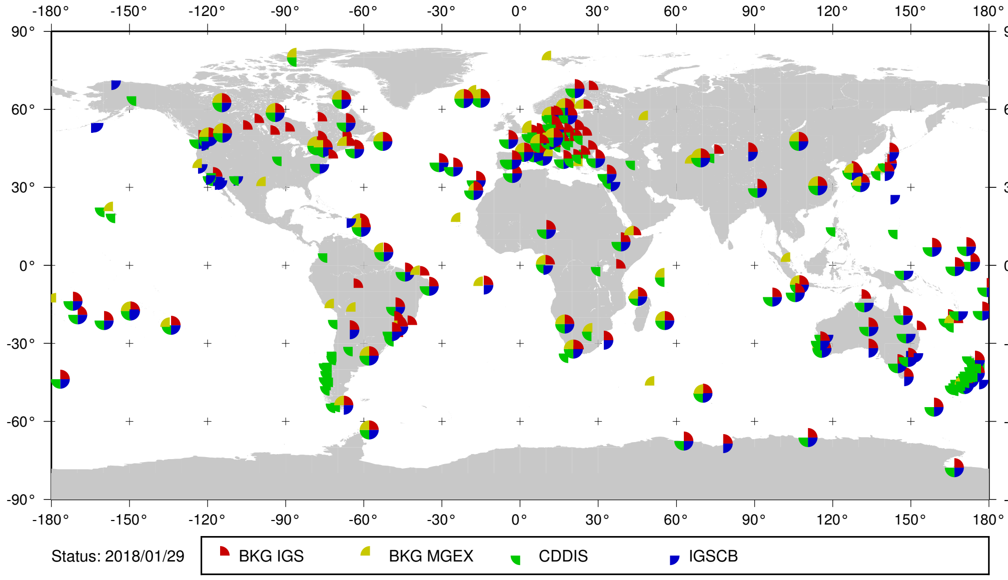

Figure 1: Station network of the IGS real time service delivered by the different first level casters (cf. Table 1).

Central Bureau Caster has been moved to the University Corporation for Atmospheric Research (UCAR). The BKG operates two different casters, the so called IGS caster and the MGEX caster. All streams on the IGS caster are receiver generated RTCM streams as supported by the receiver firmware. The streams on the MGEX caster are converted from raw data by an external software conversion tool. As soon as more receivers providing RTCM3 multi constellation data (MSM5 or better MSM7) become available the number of software generated streams will be reduced.

In addition to the three first level casters, regional caster cover a large amount of work load. Among others, regional casters are operating at Wuhan University/China and Geoscience Australia. Other regional data centres are proposed for North and South America and Europe. In order to improve redundancy in the case of failure, the station operators are encouraged to provide their data streams to at least two independent global data centres.

The caster source tables contain valuable information on the data stream content, station information and other source information. In order to keep the caster source tables consistent and up to date, DLR provided a check up tool which evaluates the source table against the stream content.

Release 2.0.29 of the BKG NProfessional Ntrip Caster Software has improved the latency of the real time data streams significantly in some cases. A remarkable improvement has been observed at the station Warkworth, New Zealand (Figure 2) where the latency could be improved by a factor of eight.

In the caster registration process additional data about the users and their purposes are collected. Figure 3 shows users affiliations and applications for the CDDIS caster at NASA. Although is no distinction between the real time observations and products the strong support of the IGS RTS for science and education becomes obvious. But there is also a significant amount of commercial users and applications.

3 Mount point naming schema

The RT-WG endorsed a new schema for naming the mount points across all IGS casters. This schema requires unique mount point names across all casters of the IGS and also promotes their use for casters of regional real time networks. The mount points should be static over time because name changes would cause problems on the user side. Additional information on the data stream content is available in the source table and does not necessarily be part of a mount point name.

The mount point should consist of the first 9 characters of the corresponding RINEXv3 filename. For the station WTZR in Germany, this 9 character code reads as WTZR00DEU. In order to distinguish different formats from the same station a number has to be added: WTZR00DEU0, WTZR00DEU1, ...

It is recommended to use "0" for the best data stream of the open RTCM3 standard (e.g. RTCM3 MSM4 or RTCM3 MSM7). This ensures, that clients can always expect an appropriate RTCM3 data stream at this mount point.

During the implementation process, a large number of mount points will be renamed across IGS casters. In a transition phase the old and the new mount point name will be available in parallel. As soon as the majority of users have switched to the new mount point, the old alias mount point can be removed.

Release 2.0.31 of BKGs Professional Ntrip caster software supports the definition of alias mount points.

4 State Space Respresentation correction streams

There are eight real time Analysis Centres (AC) which use different software packages to compute epoch-wise orbit and clock products. The large number of ACs ensures a high redundancy of the service on the one hand and a strong quality control on the other hand. The estimates are converted into RTCM SSR format and can be accessed via IGS RTS product caster at BKG and the first level casters of CDDIS and IGS Central Bureau

Table 1: First level observation broadcasters of the IGS RTS.

Data center	Caster Adress
BKG IGS-Caster	http://igs-ip.net
BKG MGEX-Caster	http://mgex.igs-ip.net
BKG Products-Caster	http://products.igs-ip.net
IGS Central Bureau	http://gnssdata-ch1.cosmic.ucar.edu
CDDIS	https://cddis-caster.gsfc.nasa.gov

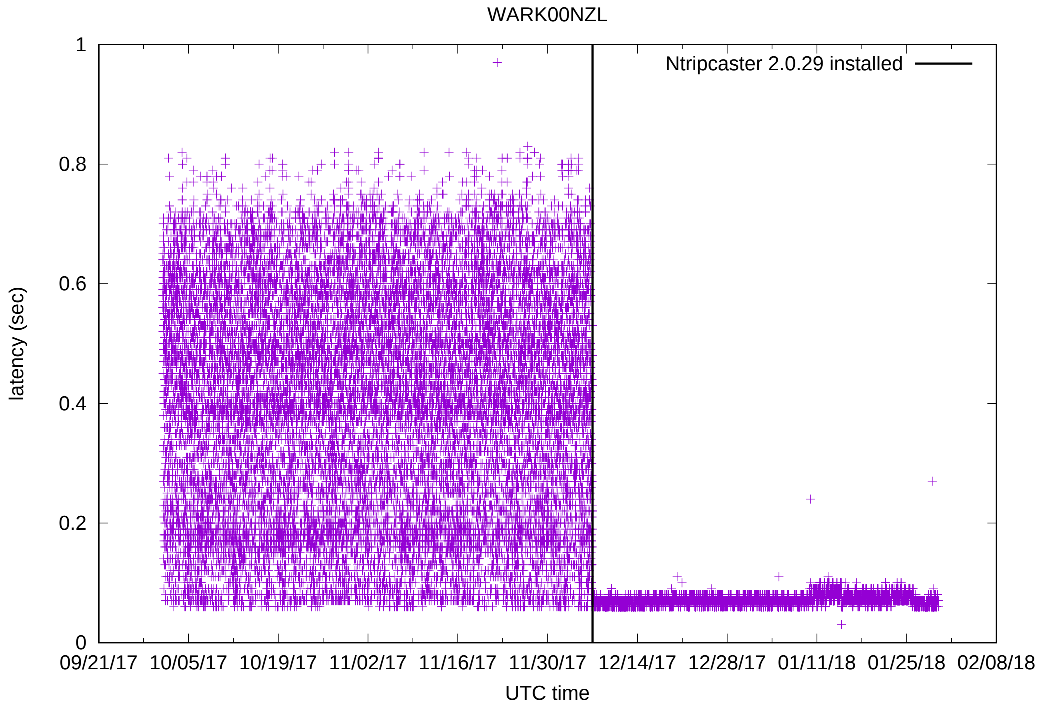

Figure 2: Latency improvement of Station Warkworth (WARK, New Zealand) after the BKG Professional NTrip Caster software has been updated to version 2.0.29 (courtesy of Elisabetta DâĂŹAnastasio, GNS Science New Zealand).

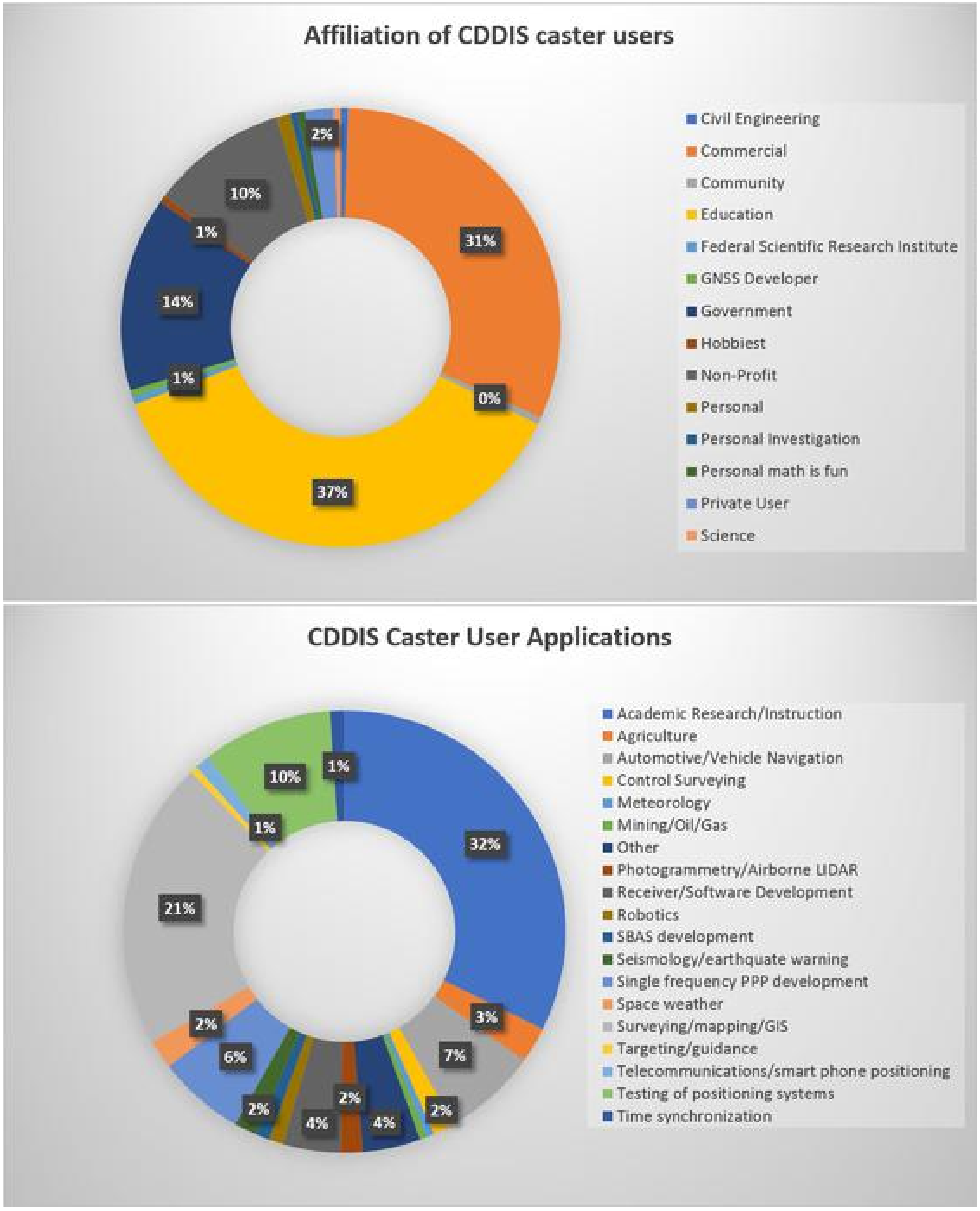

Figure 3: User affiliations and applications at CDDIS caster (courtesy of Carey Noll, CDDIS, NASA).

Figure 4: Performance of orbit and clock estimates for the IGS RTS solutions. Top: IGC01 combination orbit and clock performance for GPS, bottom: Statistics for AC and IGC03 solutions for GLONASS.

(cf. Table 1). The orbit products are available with respect to the satellite Antenna Phase Centre (APC) and in most cases they are also available with respect to the Centre of Mass (CoM). The clock products are updated every 5 seconds. In addition to GPS and GLONASS corrections, the ACs at CNES and DLR provide satellite orbit and clock corrections for Galileo and BDS. Because the SSR format description for Galileo and BDS satellite orbit and clock corrections has not yet been endorsed by the RTCM SC104 committee proposed message formats are used. Table 2 gives a summary of all individual product streams by the different ACs.

After processing the individual AC solutions in Real Time, RTS combination products are made available to users of the service (Table 3). Two basic techniques, a single epoch combination developed by ESOC and a Kalman filter based combination developed by BKG and Prague Technical University, are used. Although a combination increases the robustness of the product it also increases the latency of the combined product significantly. Since many of the individual streams have a latency of about 10s or less, the latency of the combined product is in the range of 20-30s. The reduction of latency is an important goal of the real time service and requires an optimized selection of reference stations and processing schemes. The website https://igs.bkg.bund.de/ntrip/ppp gives additional information of the actual performance of the service.

5 Summary

The observation data and products of the IGS RT Service rely on the effort of a large number of contributors: Station operators, software developers, data centers and analysis centers. Real time orbit and clock products allow users a real time positioning at decimetre accuracy using PPP.

The IGS RTS ensures open access to its data and products and supports open standards and data formats. Data and products are provided via TCP/IP connections. The range of applications is focused on scientific and educational topics, such as positioning, navigation and timing, Earth observations and research; and other applications that benefit the scientific community and society.

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Table 2: Correction streams from IGS Real Time Service by individual ACs

Center	Description	NTRIP MP CoM/APC
BKG	GPS GPS + GLONASS RT orbits and clocks using IGU orbits	CLK00/10
	GPS + GLONASS RT orbits and clocks using IGU orbits	CLK01/11
CNES	GPS+GLONASS orbits and clocks	CLK90/91
	GPS+GLONASS+Galileo+Beidou orbits and clocks	CLK92/93
DLR	GPS+GLONASS+ Galileo+Beidou RT orbits and clocks	CLK20/21
ESOC	RT orbits and clocks using NRT batch orbits every 2 hours which are based on IGS Batch hourly files	CLK50/51
	RT orbits and clocks using NRT batch orbits every 2 hours which are based on RINEX files generated from the RT stream	CLK52/53
GFZ	RT orbits and clocks and IGU orbits	CLK70/71
GMV	GPS + GLONASS orbits and clocks based on NRT orbit solution	CLK81/80
NRCan	GPS orbits and clocks using NRT batch orbits every hour	-/CLK22
WUHAN	GPS orbits and clocks based on IGU orbits	CLK15/16

Table 3: Combined correction stream by IGS Real Time Service by individual Combination Centres

Centre	Description	NTRIP MP
ESOC	GPS-only combination – epoch-wise approach	IGC01/IGS01
BKG	GPS-only combination – Kalman filter approach	-/IGS02
	GPS+GLONASS combination – Kalman filter approach	-/IGS03

Tide Gauge Benchmark Monitoring Working Group Technical Report 2017

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June 21, 2018

1 Introduction

The Tide Gauge Benchmark Monitoring Working Group (TIGA) of the IGS continues its support for climate and sea level related studies and organizations concerned herewith (e.g., GGOS, OSTST, UNESCO/IOC). The TIGA WG provides vertical geocentric positions, vertical motion and displacements of GNSS stations at or near a global network of tide gauges and works towards establishing local geodetic ties between the GNSS stations and tide gauges. To a large extend the TIGA Working Group uses the infrastructure and expertise of the IGS.

The main aims of the TIGA Working Group are:

1. Maintain a global virtual continuous GNSS @ Tide Gauge network
2. Compute precise coordinates and velocities of GNSS stations at or near tide gauges. Provide a combined solution as the IGS-TIGA official product.
3. Study the impacts of corrections and new models on the GNSS processing of the vertical coordinate. Encourage other groups to establish complementary sensors to improve the GNSS results, e.g., absolute gravity sites or DORIS.
4. Provide advice to new applications and installations.

2 Main Progress in 2017

- TIGA Working Group members actively participated in the IGS Workshop in Paris/France with several posters (see https://kb.igs.org/hc/en-us/sections/206304388-2017-IGS-WORKSHOP-Paris-France) and also in the WCRP Sea Level Conference (July, New York/USA)
- Working group meeting during the IGS Workshop in Paris/France
- TIGA Network operator continues to works with Tide Gauge and GNSS station operators to make existing stations available to TIGA, a main (ongoing) task is to update the current database of existing local ties between GNSS and tide gauge benchmarks. By the end of 2017 about 190 local ties information are available at http://www.sonel.org/-Stability-of-the-datums-.html?lang=en. The current number of GNSS@TG stations is 1071 (TIGA: 125 stations) stations (with 136 stations decommissioned).
- First Combination of TIGA solutions was performed. Not all contributions are fully integrated and some re-processing is needed.

3 Related important Outreach activities in 2017

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4 Current data holding of TIGA reprocessed individual solutions

Table 1: Current data holding of TIGA reprocessed individual solutions.

TIGA Analysis Center (TAC)	Start GPS week	End GPS week
AUT (Geoscience Australia)	0834	1891
BLT (University of Nottingham , University of Luxembourg)	0782	1722
DG2 (DGFI/TUM Germany)	0887	1824
GT2 (GFZ Potsdam TIGA Solution)	0730	1877
UL2 (University La Rochelle)	0782	1773

5 TIGA Working Group Members in 2017

Working group members are listed in Table 2.

Table 2: TIGA Working Group Members in 2017

Name	Entity	Host Institution, Country
Guy Wöppelmann	TAC, TNC, TDC	University La Rochelle, France
Laura Sánchez	TAC	DGFI TU Munich, Germany
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Minghai Jia		GeoScience Australia, Australia
Paul Tregoning		ANU, Australia
Zhiguo Deng	TAC	GFZ Potsdam, Germany
Daniela Thaller	Combination	BGK, Frankfurt, Switzerland
Norman Teferle	TAC/Combination	University of Luxembourg, Luxembourg
Richard Bingley	TAC	University of Nottingham, UK
Ruth Neilan	IGS Central Bureau	ex officio, USA
Tom Herring	IGS AC coordinator	ex officio, USA
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IGS Troposphere Working Group Technical Report 2017

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1 Introduction

The IGS Troposphere Working Group (IGS TWG) was founded in 1998. The United States Naval Observatory (USNO) assumed chairmanship of the WG as well as responsibility for producing IGS Final Troposphere Estimates (IGS FTE) in 2011.

Dr. Christine Hackman chaired the IGS TWG through December 2015. Dr. Sharyl Byram has chaired it since then and also oversees production of the IGS FTEs. IGS FTEs are produced within the USNO Earth Orientation Department GPS Analysis Division, which also hosts the USNO IGS Analysis Center.

The IGS TWG is comprised of approximately 50 members (cf. Appendix A). A revised charter approved by the IGS Governing Board at the close of 2011 is shown in Appendix B.

2 IGS Final Troposphere Product Generation/Usage 2017

USNO produces IGS Final Troposphere Estimates for nearly all of the stations of the IGS network. Each 24-hr site result file provides five-minute-spaced estimates of total troposphere zenith path delay (ZPD), north, and east gradient components, with the gradient components used to compensate for tropospheric asymmetry.

Since the implementation of the ITRF2014 reference frame in January 2017, the IGS Final Troposphere estimates have been generated with Bernese GNSS Software 5.2 Dach et al. (2015). The processing uses precise point positioning (PPP; Zumberge et al., 1997) and the GMF mapping function Boehm et al. (2006) with IGS Final satellite orbits/clocks and

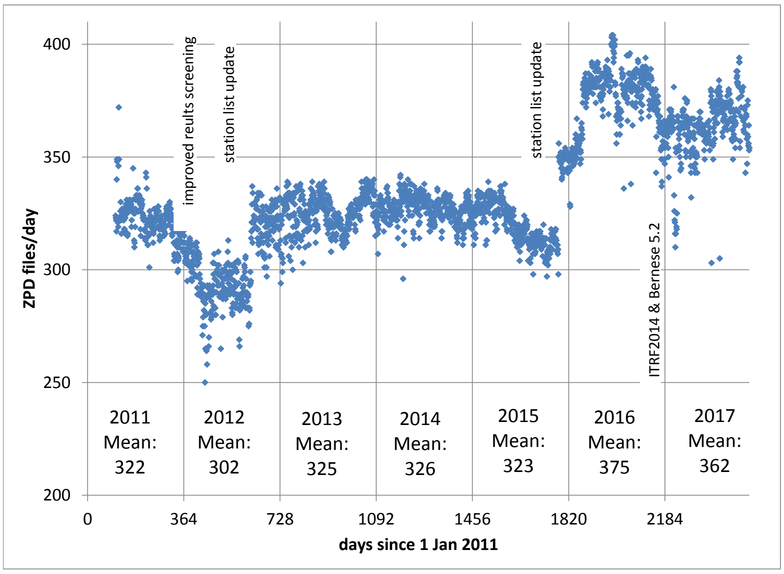

Figure 1: Number of IGS receivers for which USNO produced IGS Final Troposphere Estimates, 2011-7. (Estimates were produced by Jet Propulsion Laboratory up through mid-April 2011.)

earth orientation parameters (EOPs) as input. Each site-dayâĂŹs results are completed approximately three weeks after measurement collection as the requisite IGS Final orbit products become available. Further processing details can be obtained from (Byram and Hackman 2012).

Figure 1 shows the number of receivers for which USNO computed IGS FTEs 2011-7. The average number of quality-checked station result files submitted per day in 2017 was 362, slightly lower than the 2016 average value of 375 due to the increased number of stations switching to the Rinex 3 format. The result files can be downloaded from `ftp://cddis.gsfc.nasa.gov/gps/products/troposphere/zpd`. 24.7 million files were downloaded in 2017 by users from over 1000 distinct hosts (Noll 2016).

USNO will participate in the IGS Reprocessing 2 effort (`acc.igs.org/reprocess2.html`) contributing the Repro2 Final Troposphere estimates using Bernese GNSS Software 5.2 (`www.bernese.unibe.ch/features`) and agreed upon models and methods.

3 IGS Troposphere Working Group Activities 2017

The goal of the IGS Troposphere Working Group is to improve the accuracy and usability of GNSS-derived troposphere estimates. It does this by coordinating (a) working group projects and (b) technical sessions at the IGS Analysis Workshops.

The group meets twice per year: once in the fall in conjunction with the American Geophysical Union (AGU) Fall Meeting (San Francisco, CA, USA; December), and once in the spring/summer, either in conjunction with the European Geosciences Union (EGU) General Assembly (Vienna, Austria; April) or at the IGS Workshop (location varies; dates typically June/July).

Meetings are simulcast online so that members unable to attend in person can participate. Members can also communicate using the IGS TWG email list.

3.1 2017 Working Group Meetings

The working group met twice in 2017: in conjunction with the 2017 IGS Workshop in Paris, France, July 2017 and in conjunction with the 2017 AGU Fall Meeting in New Orleans, LA.

The July 2017 meeting featured presentations by:

- WG chair S Byram on (1) the quality and production of IGS Final Troposphere Estimates, (2) the status of current working-group projects, and (3) a discussion of future projects
- Dr. Jan Douša, Geodetic Observatory Pecny (GOP; Czech Republic) on the status of the troposphere inter-technique comparison database/website (see "Working Group Projects" below)
- Dr. Rosa Pacione on the status of the standardization of the tropo_sinex format (see ”Working Group Projects,” below)

The December 2017 meeting featured presentations by:

- WG chair S Byram on (1) the quality and production of IGS Final Troposphere Estimates, (2) the status of current working-group projects, and (3) a discussion of future projects

3.2 Working Group Projects

3.2.1 Automating comparisons of troposphere estimates obtained using different measurement or analysis techniques

One way to assess the accuracy of GNSS-derived troposphere estimates is to compare them to those obtained for the same time/location using an independent measurement technique, e.g., VLBI[1] , DORIS[2] , radiosondes, or from a numerical weather model. Comparisons of GNSS-derived troposphere estimates computed by different analysis centers or using different models can also serve this purpose.

The IGS TWG has therefore since 2012 been coordinating the creation of a database/website to automatically and continuously perform such comparisons.

Dr. Jan Douša, Geodetic Observatory Pecny (GOP; Czech Republic) has been spearheading the development of the database Douša and Gyõri (2013); Gyõri and Douša (2016), with contributions from other scientists at GOP, GeoForschungsZentrum (GFZ; Germany) and USNO. This database is now beta-complete and open for testing. Interested users can contact Dr. Douša at jan.dousa@pecny.cz. Development of the website by which users can directly view/access the values is underway. Completion of this project is expected in early 2018 when the website will be accessible to the community. This system has received interest from climatologists/meteorologists, e.g., those associated with the GRUAN and COST Action 1206 (GNSS4SWEC) projects, as it will simplify quality-comparison and perhaps acquisition of data used as input to their studies.

3.2.2 Standardization of the tropo_sinex format

The IGS Troposphere Working group also supports a project to standardize the tropo_sinex format in which troposphere delay values are disseminated. At issue is the fact that different geodetic communities (e.g., VLBI, GNSS) have modified the format in slightly different ways since the formatâĂŹs introduction in 1997. For example, text strings STDEV and STDDEV are used to denote standard deviation in the GNSS and VLBI communities respectively. Such file-format inconsistencies hamper inter-technique comparisons.

This project, spearheaded by IGS Troposphere WG members Drs. Rosa Pacione and Jan DouÅąa, is being conducted within the COST Action 1206 (GNSS4SWEC) Working Group 3. This COST WG consists of representatives from a variety of IAG[3] organizations and other communities; its work is further supported by the EUREF Technical Working Group[4] as well as E-GVAP[5] expert teams. The WG is currently defining in detail a format

[1]Very Long Baseline Interferometry
[2]Doppler Orbitography and Radiopositioning Integrated by Satellite
[3]International Association of Geodesy
[4]http://www.euref.eu/euref_twg.html
[5]EUMETNET EIG GNSS Water Vapour Programme; http://egvap.dmi.dk/

able to accommodate both troposphere values and the metadata (e.g., antenna height, local pressure values) required for further analysis/interpretation of the troposphere estimates, with progress made in 2017, and a format has been circulated for discussion/approval in late 2017. For more information, please contact Dr. Pacione at rrosa.pacione@e.geos.it or Dr. Douša.

3.2.3 Automated Analysis Center Estimate Comparisons

A suggestion was made by an IGS Analysis Center representative that the next working group project should be to re-establish the troposphere estimate comparisons for each AC. This project would consist of first comparing the Repro2 Analysis Center results in the comparison database developed by J Douša and then automating the comparison of the final troposphere estimates of the ACs as they become available. A survey asking for interest and participation in such a comparison was sent via the IGS TWG email list (message IGS-TWG-143) and AC email list (message IGS-ACS-1088).

3.3 Activities at the 2017 IGS Workshop

WG chair Dr. Sharyl Byram organized troposphere-related activities for the 2017 IGS Workshop, soliciting presentersfor the troposphere plenary and poster sessions, and holding the working-group meeting.

There were three plenary presentations as follows:

- D̈ual-layer tropospheric correction model optimally exploiting GNSS and NWM data;, J. Dousa
- Ïmprovement in the estimation of troposphere zenith delays using high-accuracy clocks;, M. Rothacher
- Ä new real-time ZTD grid product over China and applications in PPP;, W. Zhang

An additional 17 posters were presented. All presentations can be viewed at http://www.igs.org/presents/workshop2017.

4 How to Obtain Further Information

IGS Final Troposphere Estimates can be downloaded from: ftp://cddis.gsfc.nasa.gov/gps/products/troposphere/zpd

For technical questions regarding them, please contact Dr. Sharyl Byram at sharyl.byram@usno.navy.mil.

To learn more about the IGS Troposphere Working Group, you may:

- contact Dr. Sharyl Byram at sharyl.byram@usno.navy.mil,
- visit the IGS Troposphere Working Group website (under development): http://twg.igs.org, and/or
- subscribe to the IGS Troposphere Working Group email list: http://igscb.jpl.nasa.gov/mailman/listinfo/igs-twg

5 Acknowledgements

The author thanks the University of Paris Dierot for hosting the July 2017 working group meeting, IGS (especially A. Craddock) for providing a room for the (cancelled) December 2017 meeting, and the IGS Central Bureau for the use of its gotomeeting.com subscription.

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Appendix A. IGS Troposphere Working Group Members

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Amirkhani	Mohammad	Islamic Azad Univ. Tehran	Iran
Bar-Sever	Yoaz	JPL	USA
Bevis	Mike	OSU	USA
Bock	Olivier	IGN-LAREG	France
Boehm	Johannes	TU Wien	Austria
Bosser	Pierre	ENSG/DPTS	France
Bosy	Jaroslaw	Institute of Geodesy and Geoinformatics Wroclaw University of Environmental and Life Sciences	Poland
Braun	John	UCAR	USA
Byram	Sharyl	USNO	USA
Byun	Sung	JPL	USA
Calori	Andrea	Univ. Roma "La Sapienza"	Italy
Cao	Wei	Trimble Terrasat	Germany
Chen	Junping	Shanghai Astronomical Observatory	China
Colosimo	Gabriele	Univ. Roma "La Sapienza"	Italy
Crespi	Mattia	Univ. Roma "La Sapienza"	Italy
Deng	Zhiguo	GFZ	Germany
Dick	Galina	GFZ	Germany
Dousa	Jan	GOP	Poland
Drummond	Paul	Trimble	USA
Ghoddousi-Fard	Reza	Natural Resources Canada	Canada
Guerova	Guergana	Univ. Sofia	Bulgaria
Gustavson	Terry	?	USA?
Gutman	Seth	NOAA	USA
Hackman	Christine	USNO	USA
Heinkelmann	Robert	GFZ	Germany
Herring	Tom	MIT	USA
Hilla	Steve	NGS/NOAA	USA
Hobiger	Thomas	Onsala Space Observatory, Chalmers Univ. of Technology	Sweden
Januth	Timon	Univ. of Applied Sciences, Western Switzerland	Switzerland
Jones	Jonathan	Met Office UK	UK
Langley	Richard	Univ. New Brunswick	Canada
Leandro	Rodrigo	Hemisphere GNSS	USA
Leighton	Jon	3vGeomatics	Canada/UK
Liu	George	Hong Kong Polytechnic University	Hong Kong
Melachroinos	Stavros	Geoscience Australia (?)	Australia
Moeller	Gregor	TU Wien	Austria
Moore	Angelyn	JPL	USA
Negusini	Monia	Inst. Radioastronomy (IRA), National Inst. Astrophysics (INAF)	Italy
Nikolaidou	Thaleia	Univ. New Brunswick	Canada
Nordman	Maaria	Finnish Geodetic Inst.	Finland
Pacione	Rosa	ASI/CGS	Italy
Palamartchouk	Kirill	Univ. Newcastle	UK

Penna	Nigel	Univ. Newcastle	UK
Perosanz	Felix	CNES	France
Pottiaux	Eric	Royal Obs Belgium	Belgium
Prikryl	Paul	Communications Research Centre, Canada	Canada
Realini	Eugenio	GReD – Geomatics Research & Development s.r.l.	Italy
Rocken	Chris	GPS Solutions	USA
Roggenbuck	Ole	BKG	Germany
Rohm	Witold	Univ. Wroclaw	Poland
Romero	Nacho	Canary Advanced Solutions	Spain
Santos	Marcelo	Univ. New Brunswick	Canada
Schaer	Stefan	AIUB	Switzerland
Schoen	Steffen	Inst. Erdmessung, Leibniz Uni Hannover	Germany
Selle	Christina	JPL	USA
Sguerso	Domenico	Lab. Geodesy, Geomatics, GIS; Univ. Genoa	Italy
Soudarin	Laurent	Collecte Localisation Satellites	France
Teferle	Norman	Universite du Luxembourg	Luxembourg
Tracey	Jeffrey	USNO	USA
van der Marel	Hans	TU Delft	Netherlands
Waithaka	Edward Hunja	Jomo Kenyatta U. of Agriculture and Technology	Kenya
Wang	Junhong	UCAR/NCAR	USA
Willis	Pascal	Inst. de Physique du Globe de Paris	France
Xu	Zong-qiu	Liaoning TU	China
Zhang	Shoujian	Wuhan Univ.	China

Appendix B. IGS TROPOSPHERE WORKING GROUP CHARTER

GNSS can make important contributions to meteorology, climatology and other environmental disciplines through its ability to estimate troposphere parameters. Along with the continued contributions made by the collection and analysis of ground-based receiver measurements, the past decade has also seen new contributions made by space-based GNSS receivers, e.g., those on the COSMIC/FORMOSAT mission [1]. The IGS therefore continues to sanction the existence of a Troposphere Working Group (TWG).

The primary goals of the IGS TWG are to:

- Assess/improve the accuracy/precision of IGS GNSS-based troposphere estimates.
- Improve the usability of IGS troposphere estimates.
  - Confer with outside agencies interested in the use of IGS products.
  - Assess which new estimates should be added as "official" IGS products, and which, if any, official troposphere product sets should be discontinued.
- Provide and maintain expertise in troposphere-estimate techniques, issues and applications.

Science background

The primary troposphere products generated from ground-based GNSS data are estimates of total zenith path delay and north/east troposphere gradient. Ancillary measurements of surface pressure and temperature allow the extraction of precipitable water vapor from the total zenith path delay.

Water vapor, a key element in the hydrological cycle, is an important atmosphere greenhouse gas. Monitoring long-term changes in its content and distribution is essential for studying climate change. The inhomogeneous and highly variable distribution of the atmospheric water vapor also makes it a key input to weather forecasting.

Water vapor distribution is incompletely observed by conventional systems such as radiosondes and remote sensing. However, ground- and space-based GNSS techniques provide complementary coverage of this quantity. Ground-based GNSS observations produce continuous estimates of vertically integrated water vapor content with high temporal resolution over a global distribution of land-based locations; coverage is limited over the oceans (where there is no land). Conversely, water vapor can be estimated from space-borne GNSS receivers using ray tracing techniques, in which case solutions with high vertical resolution (laterally integrated over few hundred kilometers) and good oceanic/land coverage are obtained; these solutions however are discontinuous in geographic location and time.

Be it resolved that the IGS troposphere WG will:

- Support those IGS analysis centers providing official IGS troposphere products.
- Increase awareness/usage of IGS troposphere products by members of the atmospheric, meteorology and climate-change communities. Solicit the input and involvement of such agencies.
- Create new IGS troposphere products as needed (as determined by consultation with the potential user community).
- Determine the uncertainty of IGS troposphere estimates through comparison of solutions with those obtained from independent techniques, or through other means as appropriate.
- Promote synergy between space-based and ground-based GNSS techniques through interaction with researchers in both fields.

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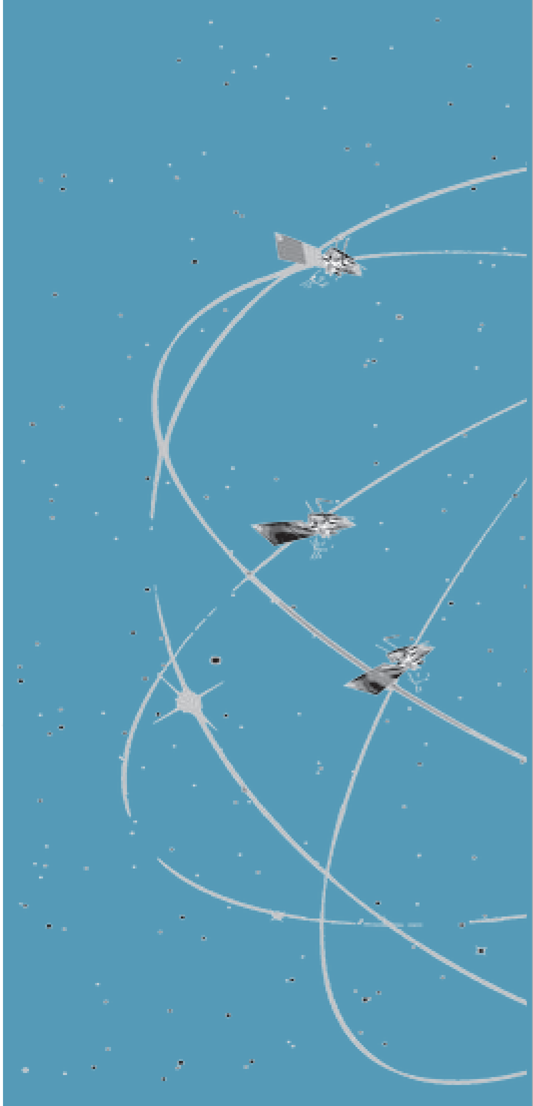

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